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ROCKALL CONTINENTAL MARGIN PROJECT

AN INVESTIGATION OF THE QUATERNARY SEDIMENTS FROM BGS BOREHOLES 99/3, 99/4, 99/5 AND 99/6, FAROE – SHETLAND CHANNEL

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Executive Summary

An investigation into the sedimentology and depositional environments was carried out on cores retrieved from 4 boreholes in the Faroe-Shetland Channel, west of Shetland. The study showed the area around boreholes 99/3 and 99/6 had been subjected to a glacial influence since the mid-Quaternary. This influence comprised a build-up of glacial sediments at the edge of the continental shelf which periodically became unstable, resulting in repeated mass flows down the continental slope. Sediments deposited between these events shows there was also current activity at the seafloor during this period. The area further west around boreholes 99/4 and 99/5 show a greatly reduced glacial influence, deposition being dominated by seafloor currents. As a result of the mixed nature of the sediments, accurate dating is difficult and consequently it is uncertain when the mass flow events last occurred.

1.0 Introduction

An investigation of the Quaternary sediments from a series of boreholes in the Faroe-Shetland Channel was undertaken on behalf of the GEM consortium. The main purposes of this study were the characterisation of the lithologies and the identification of depositional settings for the Quaternary sediments in the area and if possible, to further constrain their depositional age.

The 4 boreholes covered by this report lie at the SW end of the Faroe–Shetland Channel in the region of the Judd Deeps and the Wyville-Thomsom Ridge (Figure 1). They were drilled by the British Geological Survey for the Rockall Consortium in 1999 as part of a wider survey, which also identified the base of the Quaternary sections from microfossil evidence. Seismic data and gravity cores were obtained from the borehole locations during drillsite surveys in 1998.

1.1 Geological setting.

The boreholes lie in water depths of between 700m and 1200m in an area which has been subjected to a glacial influence since the late Pliocene, although this was restricted to distal ice-rafting until the mid-Pleistocene when major ice sheet development began (Boulton, 1991). The first major glacial advance, during the Anglian Stage, may have led to the ice front reaching the shelf edge (Stoker, 1990). The effect of this was to deliver large volumes of debris directly to the shelf edge and upper slope which allowed the development of a substantial wedge of ice-derived sediments. Periodically this wedge became unstable, leading to the formation of debris flows and turbidites which reached the slope break and occasionally the floor of the Faroe-Shetland Channel (Stoker et al, 1991) However, the majority of sediments reaching the deep water areas were derived from ice rafting.

Analysis of the present sea-floor morphology of the Faroe-Shetland Channel shows the existence of an extensive slope apron composed of numerous coalesced fan-like lobes developed along the slope base (see figure 2). Borehole 99/3 lies within the area of the slope apron, and analysis of the seismic data related to this site indicates that this style of sedimentary architecture is present throughout the Quaternary section. Dating of these sediments is difficult due to their re-worked nature and their glacial origin, containing a mixture of material from all the rocks over which the ice sheet passed.

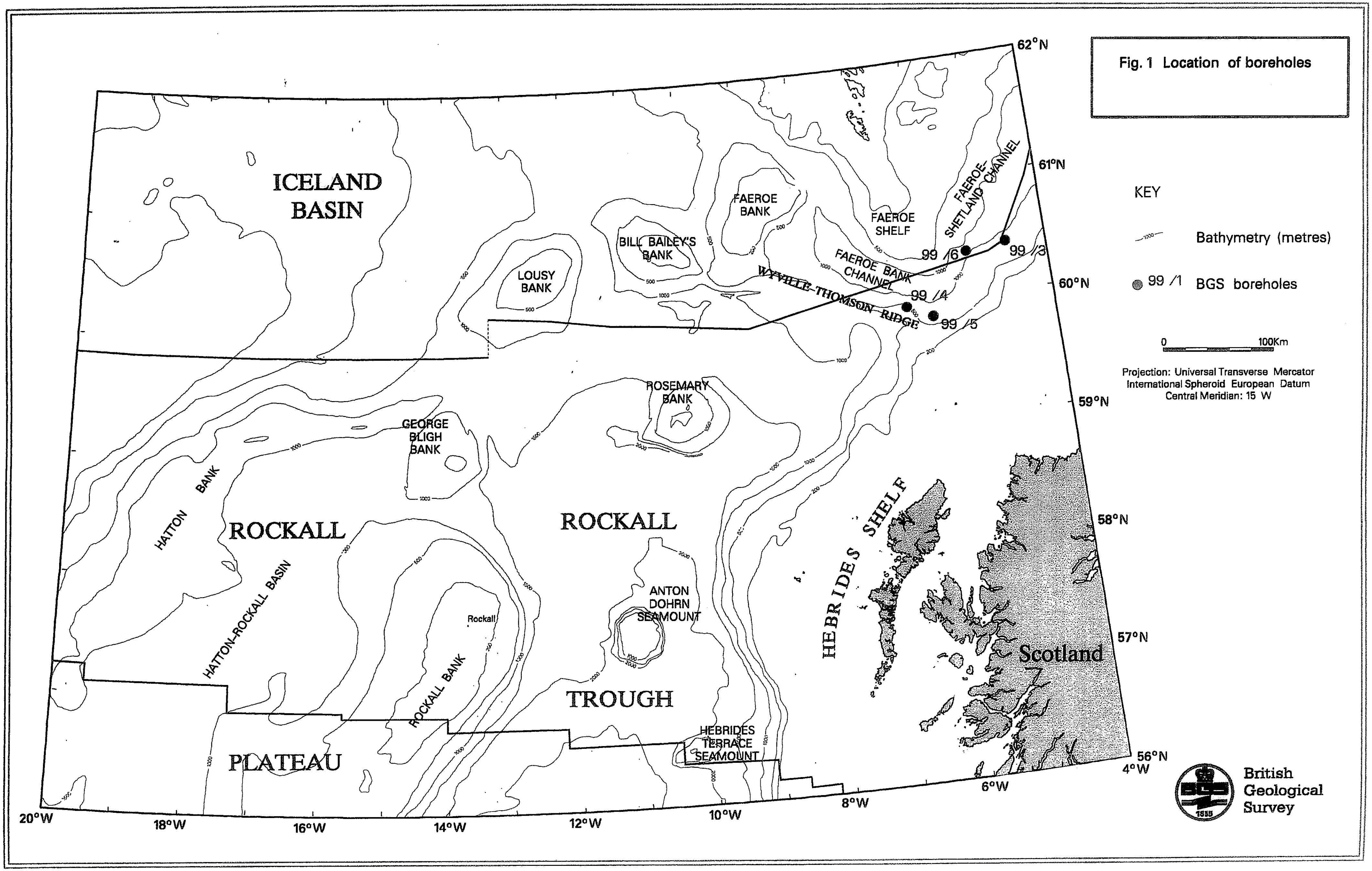


Fig. 1 Location of boreholes

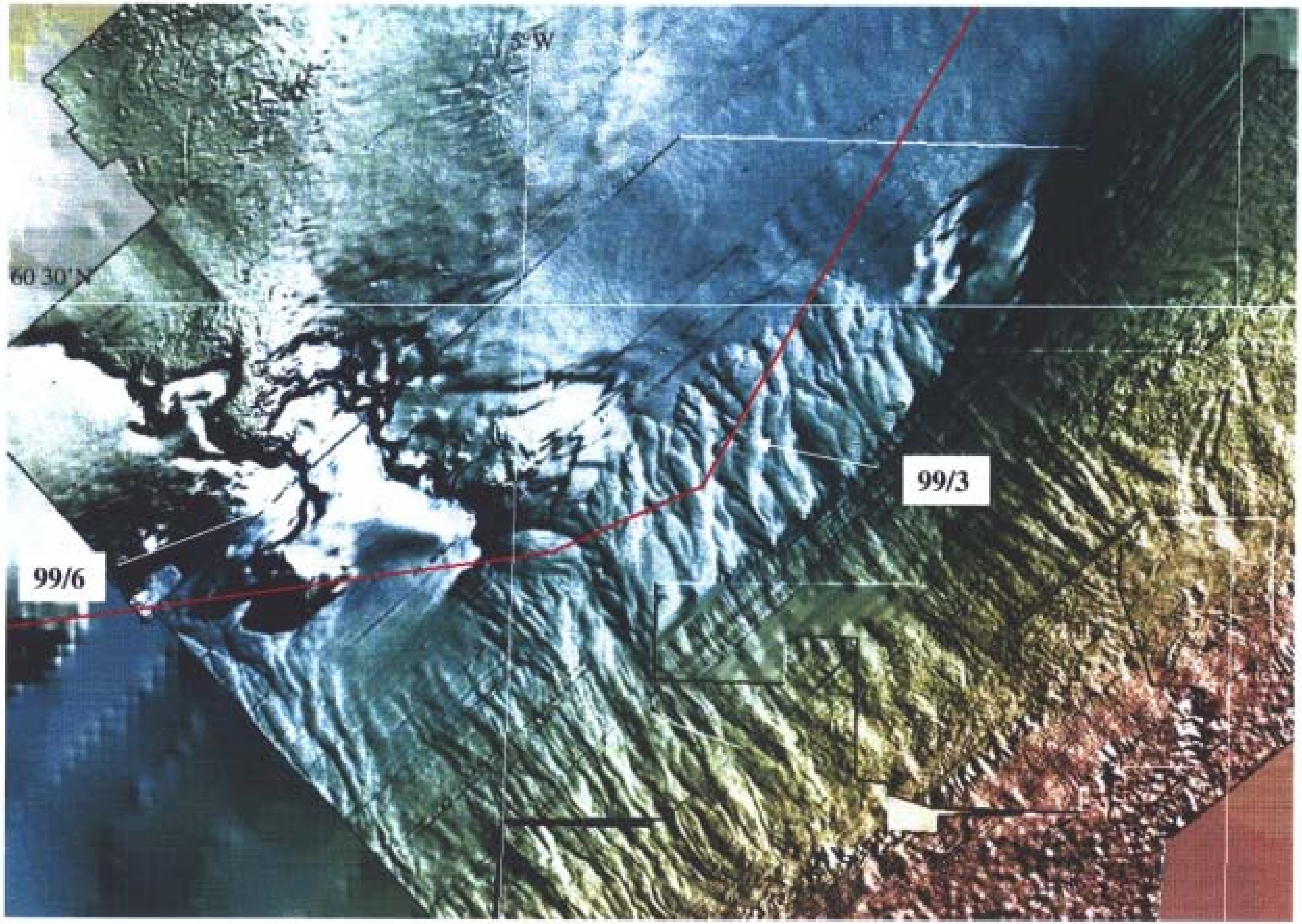


Figure 2. Seabed image, Faroe-Shetland Channel. Illuminated from the NE. Scale approx 1:454 000

2.0 Methodology

The cores examined for this report were drilled by the *MS Bucentaur* during June and July 1999 using a rotary drilling method producing a core with a diameter of 3". Drill-site seismic data and gravity cores were obtained on an earlier cruise in 1998 by the *RRS Challenger*. Information from the gravity cores was combined with that from the drilled cores as the drilling recovered no material above a depth of approximately 3m.

2.1 Core Analysis

Analysis of the cores was carried out by visual examination for identification of lithology, mineralogy, grain morphology, sedimentary structures, colour (using standard "Munsell" soil colour charts) and biogenic material. Grain size was determined by visual estimation under a binocular microscope with the aid of a set of in-house standard samples. Due to the cohesiveness of many of the lithologies and time constraints, sieving of the sediments was not undertaken. A visual test for carbonate content was also performed with dilute hydrochloric acid.

2.2 Sedimentary Logs

Sedimentary logs from analysis of the cores are presented in section 4 of this report. The logs record lithology, grain size, depth, recovered intervals and depths of samples taken for micropalaeontological analysis. A detailed description of each lithology is also included on the logs together with a facies type. Detailed descriptions of the facies groups and interpretations of the depositional settings are presented in section 3. Where possible, the position of seismic package boundaries are also recorded on the logs. Results of geotechnical tests performed on the sediments are included within the descriptions on the logs.

2.3 Geotechnical Tests

Geotechnical tests were performed, where possible to measure unconfined shear and compressional strength of the sediments. Testing took place in March 2000, approximately 8 months after drilling. Some draining of the cores occured during storage but this was mostly confined to the sandy units. Those with a higher mud content had drained little in this time.

Shear tests were carried out using a Soiltest CL-600A torvane. Compressional tests were performed using a pocket penetrometer. Where bed thickness and lack of disturbance allowed, a 25cm^3 cylinder of sediment was removed, weighed and placed in a drying oven for 24 hours at 110° C in order to measure water content.

The recovered sections of unconsolidated and free draining sands were generally not subjected to the geotechnical testing. Many of these intervals showed evidence of possible reworking and homogenisation during drilling and the results obtained would therefore be unrepresentative of the true nature of the sediments. Disturbance and cracking due to dehydration was present in some of the muddier units. In extreme cases reliable tests could not be performed. The results of the tests are presented in tables 1 and 2 (overleaf).

2.4 Core X-ray analysis

Undisturbed sections of core were subjected to x-ray photography in order to search for sedimentary and biogenic structures. Cores were x-rayed using a Scanray AC120L instrument. A combination of whole and split cores were X-rayed using a range of exposure times of up to 3.5 minutes.

A total of 34 x-ray photographs were taken and examined for structures. Unfortunately no structures were found other than pebble clasts which could be identified without x-rays. The results showed no evidence of stratification or biogenic structures. The resulting x-ray images also proved too dark to usefully print, and as they revealed nothing of sedimentological value it was decided not to print them.

Table 1. Geotechnical results for borehole 99/3

Sample depth in metres	Bulk density in Mg/m^3	Dry density in Mg/m^3	% water content	Shear strength from Torvane in kPa	Shear strength from Penetrometer in kPa
*0.93				4.4	5.7
*1.93				6.4	8.3
7.70	2.28	1.74	30.8	6.0	5.4
12.85	2.56	2.15	19.2	16.0	25.0
28.80	2.53	1.85	27.4	30.0	60.0
34.44	2.24	1.70	32.3	23.0	42.5
34.78				26.0	52.5
37.70	2.14	1.59	34.6	30.0	31.3
37.90				30.0	55.0
41.04	2.54	2.12	20.7	26.0	35.0
43.20	2.13	1.81	17.7	26.0	125.0
43.54				15.0	15.0
44.03	2.41	2.03	18.7	22.0	18.0
44.37	2.35	1.95	20.8	26.0	31.3
45.62	2.39	1.94	23.3	15.0	13.0
46.20				18.0	15.0
46.60	2.46	1.99	23.3	12.0	17.5
47.30	2.06	1.45	42.6	31.0	25.0
50.30	2.11	1.46	44.0	23.0	21.0

* Denotes tests carried out on gravity core in 1998

Table 2. Geotechnical results for borehole 99/6

Sample depth in metres	Bulk density in Mg/m^3	Dry density in Mg/m^3	% water content	Shear strength from Torvane in kPa	Shear strength from Penetrometer in kPa
*0.60				4.0	6.7
*1.20				6.2	7.5
3.80	1.98	1.26	56.6	2.0	< 0.5
4.65	1.93	1.33	44.5	9.5	18.25
4.80	2.26	1.68	34.0	14.5	25.0
4.88				14.0	10.0
4.94	2.23	1.59	40.2	12.0	15.0
9.35				5.0	7.5
9.60	2.01	1.37	46.3	12.0	15.0
9.95	2.13	1.54	38.3	11.0	15.7
11.97				8.0	35.0
13.50	2.12	1.69	25.3	5.0	50.0
13.95	1.87	1.20	56.3	7.5	5.0

Table 3. Geotechnical results for borehole 99/5

Sample depth in metres	Bulk density in Mg/m^3	Dry density in Mg/m^3	% water content	Shear strength from Torvane in kPa	Shear strength from Penetrometer in kPa
*3.10				5.0	25.5
*3.70				5.0	22.5
30.83	2.19	1.69	29.2	47.0	115.0

* Denotes tests carried out on gravity core in 1998

3.0 Facies descriptions:

3.1 Facies A

Facies A consists predominantly of unconsolidated sands and gravel with a low or absent mud content. In some sections only pebbles and cobbles were recovered which, in the absence of other evidence, are also assigned to this facies. Observed thickness of this facies reaches a maximum of 2.75m, although the inferred thickness is up to 12m. Individual bed thicknesses are difficult to define but may reach up to 1.2 m in borehole 99/6. Bed contacts with other lithologies are only observed in two sections, both of which are too disturbed for accurate description. However, the contact at 13.75m in borehole 99/6 suggests a rapid transition or planar contact as opposed to a gradational contact. Most of the recovered sections of facies A show little sign of internal structure except for the section 11.03m – 13.75m from 99/6. This section shows two poorly defined bands of muddier sand approximately 15 – 25cm thick, separated by a matrix-poor sand. The facies A units 2.96 – 3.78m, 16.66 – 17.40m and 21.55 – 22.00m in borehole 99/5 show a general fining upwards within the recovered interval. The lowermost of these also has a higher mud content (up to 30%) than other facies A units, but is classified as facies A on the basis of its coarse sandy and pebbly nature and the grading.

The sand fraction of facies A has a ratio of about 70:30 quartz grains to lithic grains with a wide range of grain sizes from fine sand to granular sand. The proportion of lithic grains increases with increasing grain size up to about 50% in some of the granular sands. Grain morphology also shows considerable variation from angular to well rounded. A high proportion (approx. 20-40%) of quartz grains show evidence of an iron oxide coating which pre-dates deposition. This coating is more common within the subangular to angular grain population. Lithologies of lithic grains within these sands include red and green sandstones, limestone, gneiss, amphibolites, garnet and basalts. The lithologies present in the pebble suite of this facies reflect those of the lithic grains. The degree of roundness in the pebbles increases with diameter, the average being approximately 10 - 20mm and sub-rounded to rounded. Bioturbation was not observed within this facies. This may be due to absence, lack of preservation or destruction during coring.

Interpretation

The general coarse-grained and matrix-poor nature of facies A tends to indicate the presence of current activity which either prevented original deposition of fine sediment, or which removed the finer grain sizes during post-depositional re-working. It is possible that some reworking and removal of the fine fraction occurred during drilling. However, results from the microfossil analysis of 99/3 indicate that the abundance of foraminifera varies between fossil-rich and barren intervals within the sands, which would not be expected if homogenisation had occurred during drilling. The presence of alternating muddy and matrix-poor horizons within 99/6 also suggest the structure is probably original.

The relative abundance of planktonic foraminifera in the matrix-poor horizons suggests a concentration of microfossils by current winnowing, removing the mud matrix from these units and leaving them relatively enriched in microfossils. This re-working was then followed by another pulse of sediment input. Selective removal of foraminifera from the matrix-rich horizons is not thought possible as any current with a velocity great enough to remove the forams would also have removed the mud and silt-sized sediment fraction. This style of deposition is compatible with current deposited sediments from turbidity currents or from bottom current activity. Given the differences in grain size of units in this facies, deposition by turbidity currents seems more likely. Both processes are known from glaciomarine settings (e.g.: Hambrey, 1994. Ackhurst, 1991) which is a likely scenario when the Quaternary age and geographical position of these sediments are considered.

3.2 Facies B

Facies B is characterised by a mud content of at least 70%, and reaches as high as 95% in some units. The majority of horizons within this facies group are dark grey-green or occasionally grey-brown. Sand content is generally low, with the bulk of the non-mud fraction being composed of fine silt. The sand that is present has a modal grain size of fine to very fine, but with a range from very fine to granular. Observed thickness of units in facies B varies between 0.14m and 0.8m. The inferred thickness is up to 4m. Where visible, the lower boundary of facies B units is gradational over 2-5cm with the underlying facies.

Quartz grain morphology is subangular to subrounded. A small proportion of the larger quartz grains possess a coating of iron oxide. Lithic grains form no more than 30% of the total sand fraction, and average about 15%. Carbonate content of this facies is quite variable and appears to be related to the proximity of individual units to the carbonate-rich diamicton units of other facies and the percentage of coarse sediment. No internal structure of either sedimentary or biogenic origin was observed within any of the units of facies B

Interpretation

The fine grained nature of this facies indicates that there was little or no current activity operating at the time of deposition. The absence of lamination or trace fossils within these units is unexpected, but suggests that rates of deposition may have been high. It seems unlikely that bioturbation has completely destroyed the original structure and left no trace of biological activity. The other possibility is that biological activity was inhibited by a factor such as a restricted oxygen level. This possibility is supported by the grey-green colour of the mud indicating reducing/low oxygen conditions.

A high rate of deposition, and the clastic nature of the sediments, indicates that the muds are not solely the product of normal background marine deposition and that these sediments are probably the result of distal clastic input from a terrestrial source. The coarse sediment in the muds is incompatible with the lack of current activity and suggests an additional source of clastic material. The absence of coarser horizons and the homogenous distribution of sand within the muds, discounts the possibility of the sand being a lag deposit formed by winnowing. The most likely origin of the coarse sediment fraction is from ice rafting. The presence of a cold water (arctic) microfossil fauna also supports this interpretation (see micropalaeontology report, Appendix 1). The lack of significant quantities of sand and the scarcity of pebbles, indicates that this material was being delivered close to the limit of influence by ice rafting and the ice front was some distance away. The mud fraction is probably the result of a combination of ice rafting and deposition from suspension, the suspended sediment being derived from meltwater input at the distant ice margin and possibly from turbidite/debris flow activity further up the slope.

3.3 Facies C

Facies C is composed of predominantly red-brown, matrix-supported sandy diamicton. These units are characterised by a mud content of between 50% and 70%. The sand content varies between 30% and 45%, the remainder being composed of larger, pebble sized clasts. Sand grain size shows a wide variation from granular to very fine. However the dominant grain size lies between very fine to medium. The thickness of units from facies C reaches a maximum of 1.46m, although the inferred thickness is up to 4.50m. Only core recovered from the interval 12.63 – 13.00m in borehole 99/3 shows the lower contact of a facies C unit. This suggests the boundary is gradational over 2-3cm rather than a sharp contact. Within facies C there is no evidence of internal structure of either biological or sedimentary origin.

The lithic grain component of the sand fraction reaches a maximum of 65:35 quartz : lithics, although a ratio of 80:20 is more typical. Quartz grain morphology spans a range from angular to rounded, and provides limited information with regard to transport and depositional processes. Texturally this facies is mud supported and very poorly sorted. The matrix also contains a significant proportion of carbonate. The pebble content of these diamictons varies from pebble free to about 5%, with pebbles averaging 15mm. The main lithologies present in the pebble suite are acidic gneiss, amphibolite, red sandstones and siltstones, grey quartzite and dolomitic limestone. The two facies C intervals between 47.50m and 38.79m in borehole 99/3 show an apparent increase in density when compared to the diamictons and muds of other facies. This difference appears to be related to greater compaction, possibly caused by settling, which is indicated by a water content which is generally lower than other lithologies.

Interpretation

The poorly sorted and structureless nature of this facies indicates that deposition was probably rapid. The compositional and textural features of these diamictons are characteristic of glacial tills and debris flows. The presence of an arctic water microfossil assemblage indicates glacial conditions were operating at the time of sediment formation. The foraminifera forming this assemblage are characteristic of shallow inner shelf environments, so their presence in a deep water slope setting strongly supports the possibility that the facies C sediments are not in situ. Lithologically, it is not possible to determine whether this facies represents a glacial till or a debris flow. However, when combined with seismic data and bathymetry from the borehole areas it is possible to define this facies as being a debris flow derived from glacial sediments (see borehole interpretation, section 4). The likelihood of a till deposit forming at the base of the slope would require a drop in sea level of over 800m, which is not thought to be a credible possibility. The seabed morphology (Figure 2) also strongly supports a debris flow origin and discounts the possibility of the sediments being an in-situ till.

3.4 Facies D

The lithology of facies D is very similar to that of C in that it is also a structureless diamicton showing a very poor degree of sorting. The main difference between the two facies is the mud to sand ratio. Facies D is characterised by a mud content of approximately 70% with a low sand content of no more than 10%, the remainder being mostly silt. Sand grade sediment is dominated by quartz, with lithic grains forming only about 10% of the sand fraction. Rare pebbles up to 30mm, and very rare cobbles up to 110mm occur throughout this facies as isolated clasts. The majority of these clasts are composed of sandstone or amphibolite. The maximum observed thickness of facies D is 0.80m. The inferred thickness may be as great as 21.0m, but this is difficult to prove.

Analysis of the microfossil content of this diamicton shows the presence of a cold water foraminifera assemblage. The sediments also show a mixture of shallow and deep water species.

Interpretation

An interpretation of depositional processes based upon lithology is difficult due to the generally poor recovery from within this facies. Broadly the possibilities are the same as for facies C in that deposition from ice or from a debris flow could produce the observed lithology. The higher mud and lower sand content suggests that which ever process was responsible for the deposition of this facies, it probably originated in a more distal setting than facies C. Integration with the seismic data from borehole 99/3 indicates a debris flow origin for facies D (see section 4.1.5 and figures 4 and 5). The presence of a mixed deep and shallow water foraminifera assemblage indicates an input of re-worked sediments from higher on the slope or from the shelf. This is compatible with facies D being deposited by debris flows derived from glacial sediments deposited on the upper slope and outer shelf.

3.6 Facies E

Facies E consists of sandy mud with a small percentage of pebbles. The distinguishing feature of this facies is the fining upwards nature of the sediment. Mud content is between 60% and 80%, with sand decreasing upwards. The proportion of lithic grains in the sand fraction reaches approximately 15% and includes a wide variety of lithologies. The basal boundary of units from within this facies is notably sharp. Whilst this type of fining upwards facies is only seen in detail in borehole 99/6, it is possible that some of the sandy intervals in other boreholes may be derived from a similar depositional setting but the incomplete core recovery masks their true nature. Observed thickness of facies reaches 1.64m, with individual beds of up to 0.90m.

Interpretation

The fining upwards nature and the sharp basal boundary of units in facies E are important characteristics which indicate deposition from an event with a waning current. These features, combined with the sandy mud composition of the sediments is typical of a turbidite deposit formed from downslope turbidity currents. The presence of a limited deep water fauna suggests some of the sediments may have been derived locally.

3.7 Facies F

Facies F is unique to borehole 99/4 and consists of amygdaloidal basalts and green muds. The muds contain basaltic pebbles and sand in various stages of decay. Basalt pebbles within the muds are surrounded by a zone of friable basalt and muddy basaltic sand. Within the muds there are thin horizons of white crystalline debris which appears to be weathered out amygdales from the basalts.

Interpretation

The green muds are a weathering product of the basalts. The presence of the weathering zones around the basalt pebbles indicates that this decay is in-situ and the amygdaloidal horizons represent concentration bands formed as the bulk of the basalts decay leaving the more resistant calcareous amygdales.. The presence of the muds suggests that there was little current activity at the time of formation as there is no evidence for the removal of the mud, although the basalt decay may have taken place following burial by other sediments which prevented removal of the muds.

BOREHOLES

4.0 Boreholes

The borehole descriptions and interpretations are arranged in as separate sections. Each section includes a detailed sedimentary log of the core, some or all of the drill-site survey seismic data and an interpretation of the sedimentology and depositional setting.

The sedimentary logs indicate lithology, depth, recovered intervals, grain size, facies group and a detailed description of each lithology. Where a lithological boundary occurs in an interval of no recovery, the boundary is taken as the mid-point between the two, unless other information such as seismic or drilling data enables a more accurate fix to be made. Recovered intervals are indicated by the black sections in the recovery column of the logs.

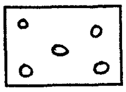
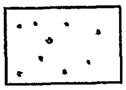
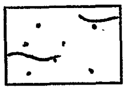
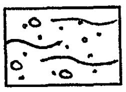
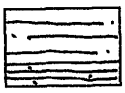
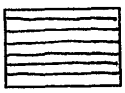
Seismic survey data from drill-site hazard investigations is included to aid and enhance interpretations.

NB: The geotechnical data given on the logs should be interpreted as;

Shear strength	- shear strength obtained from use of a torvane
Compressive strength	- shear strength obtained from a pocket penetrometer
Water content	- Water content as a percentage of the bulk sediment

Key to symbols used in borehole logs

Lithologies

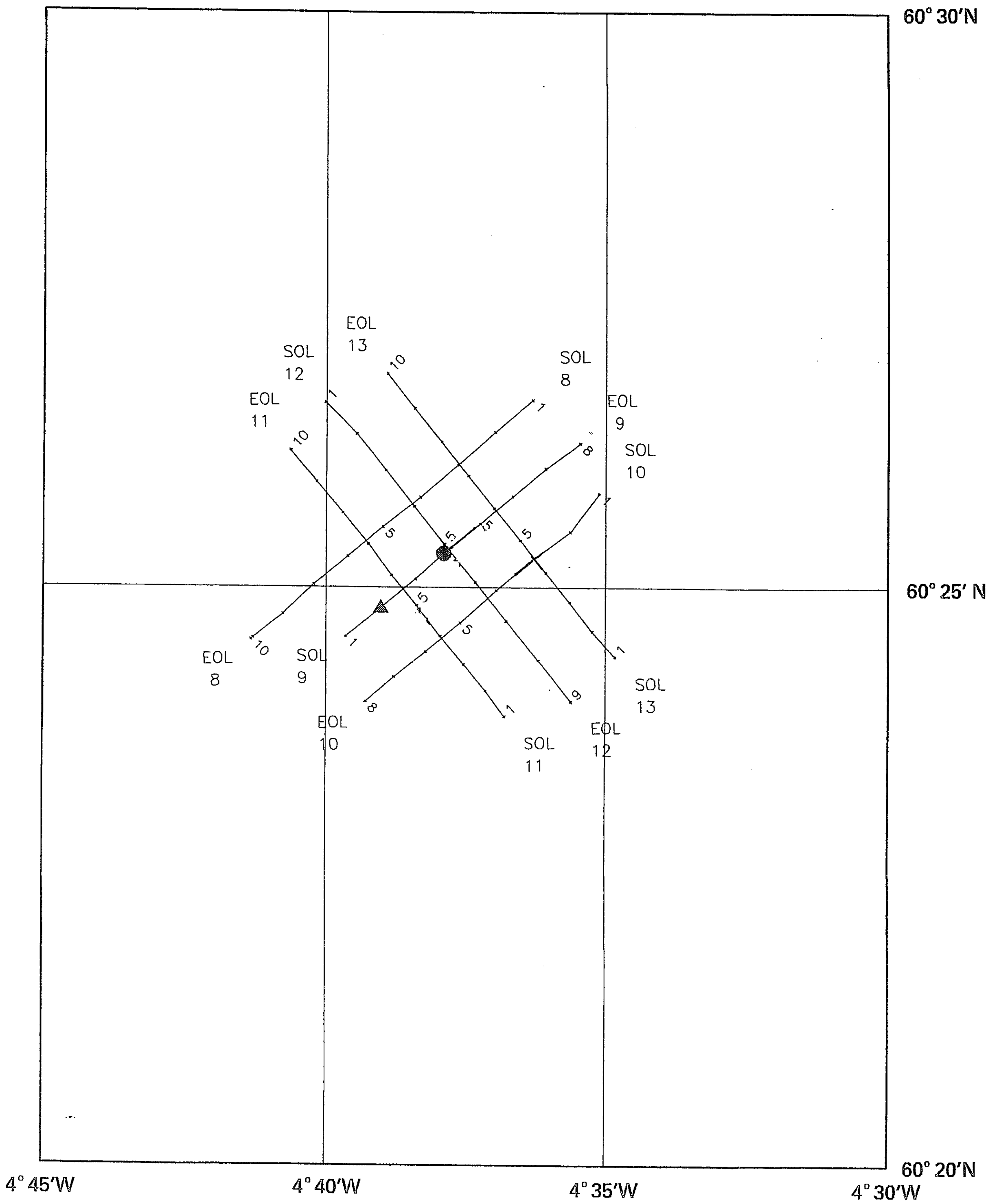
	Gravel
	Sand
	Muddy sand
	Diamicton
	Silty mud
	Mud
MP	Micropalaeontology sample
VI	Seismic package number (99/3 only)
	Shell debris
	Trace fossils
A	Lithofacies group

Borehole 99/3

Location:	SE flank of Faroe-Shetland Channel, c.75km WNW of Foula
Latitude:	60° 24.819' N
Longitude:	04° 39.064' W
Map Area:	Judd
Block No.	204/17
Date of drilling:	20-24th June 1999
Water Depth:	983m
Total depth:	166.5m
Depth to base of Quaternary:	c.56m

Gravity core No.	60-05/142
Latitude:	60° 25.30' N
Longitude:	04° 37.89' W
Date of sampling:	31st May 1998
Water depth:	983m
Total depth:	1.93m

Figure 3. Location of sparker survey lines for borehole 99/3.



Location of gravity core (seabed sample)

Location of borehole

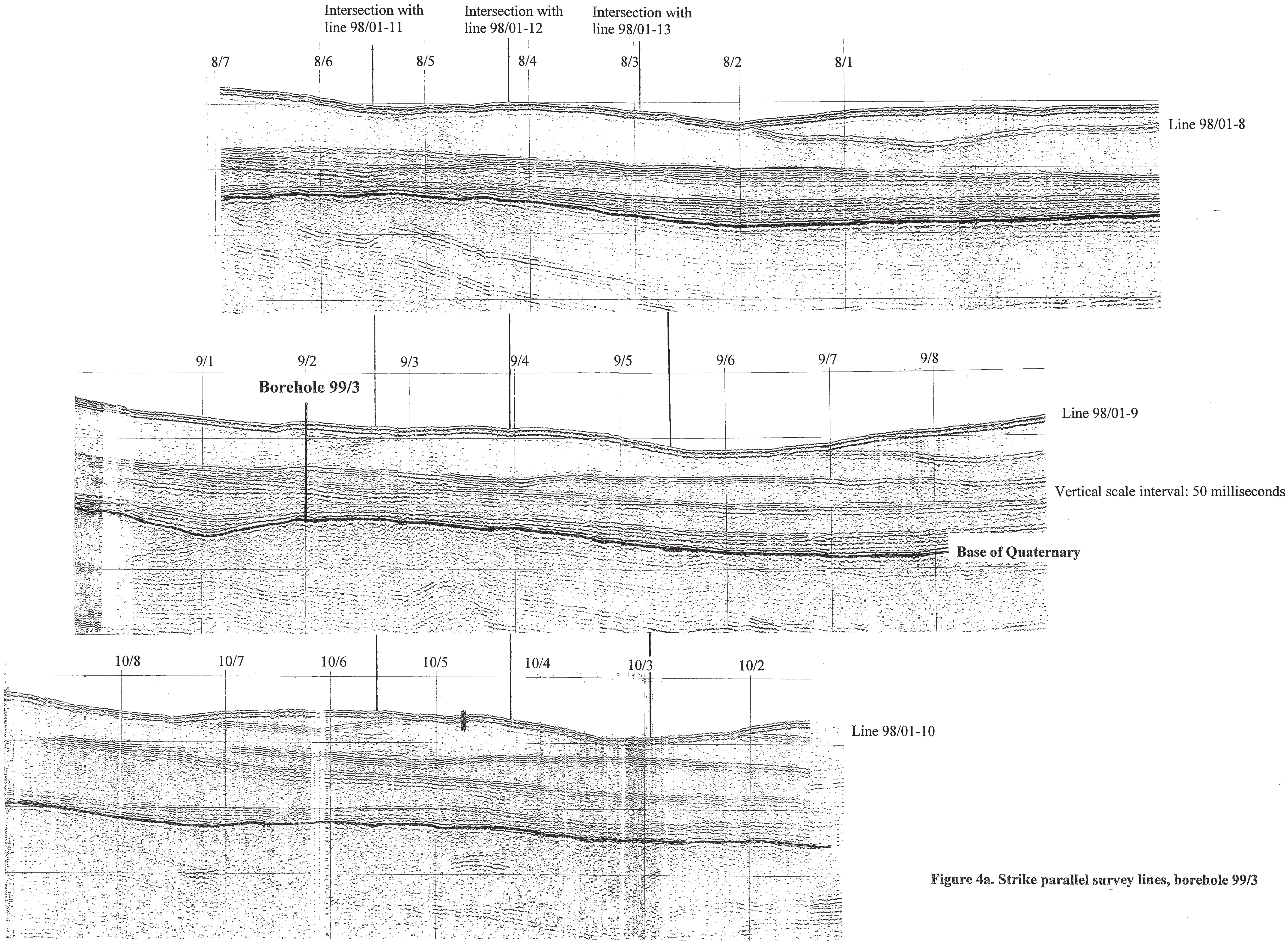


Figure 4a. Strike parallel survey lines, borehole 99/3

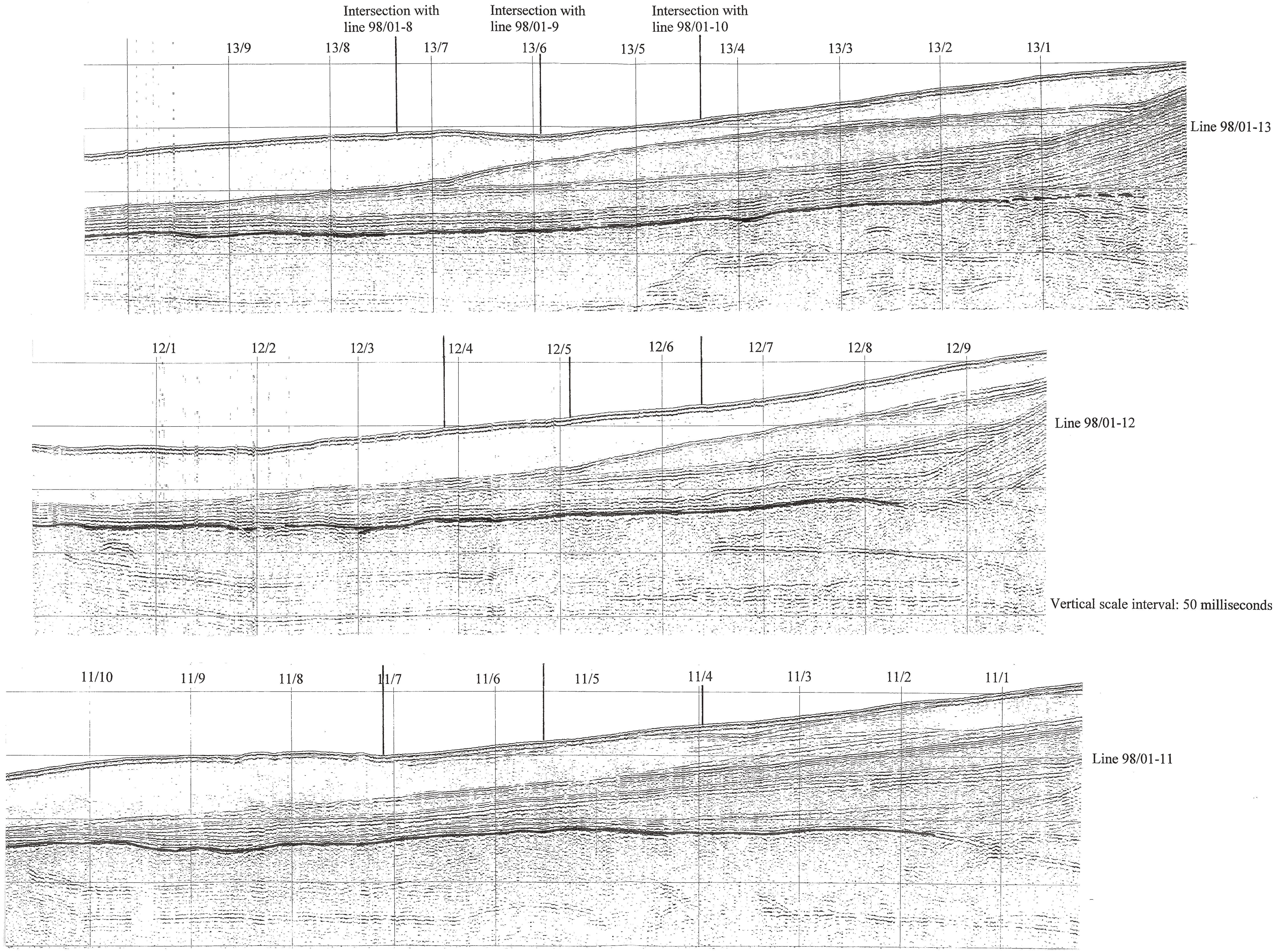
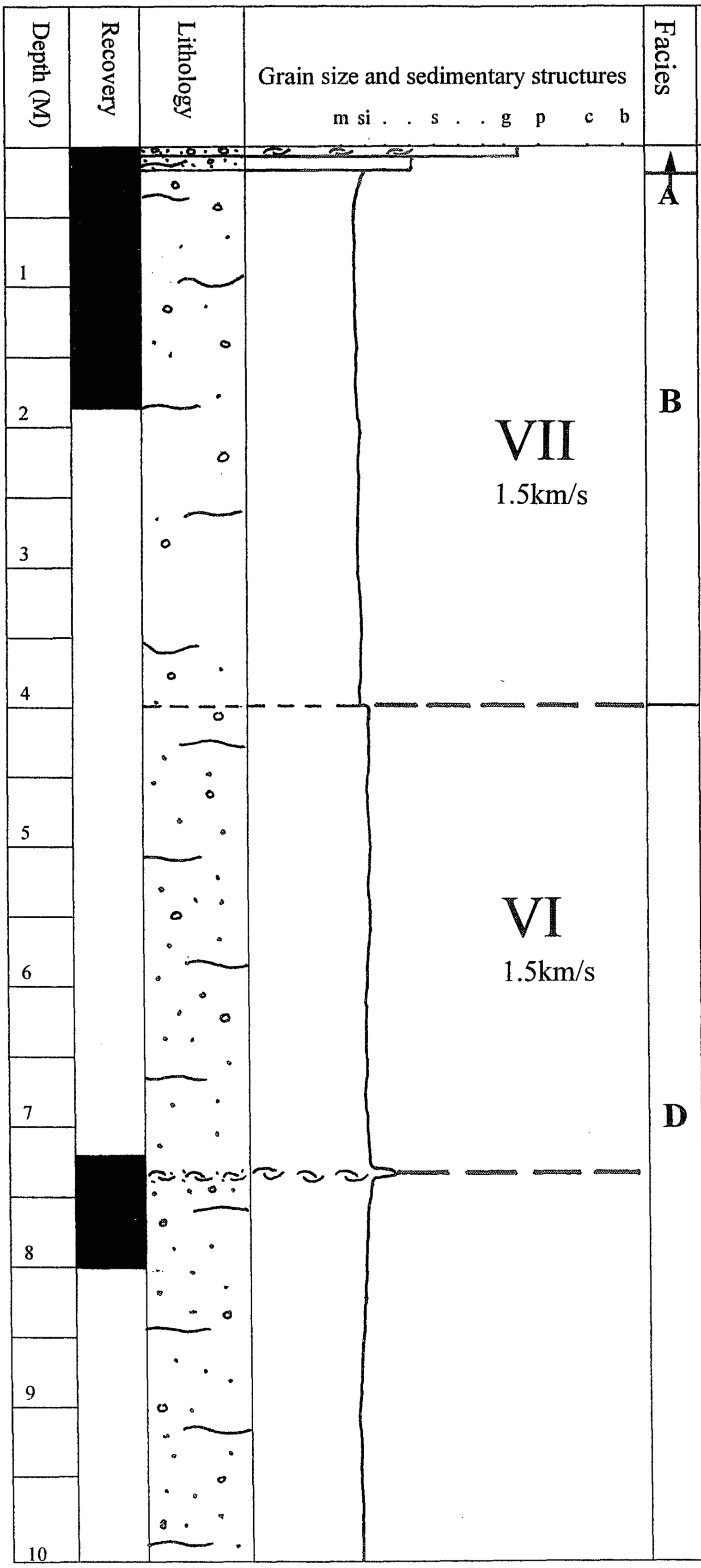


Figure 4b. Dip parallel survey lines, borehole 99/3

Scale 1:50



Description

0 – 1.93m Gravity core data

0.0 – 0.05m Sandy gravel. Dark grey-brown (10YR4/2). Very poorly sorted, very fine to very coarse sand with angular to subrounded gravel, clasts up to 45mm composed of sandstone and gneiss. Sand approx. 50% subangular to rounded quartz, 30% lithic grains and 20% shell material. Abundant foraminifera. Sharp basal contact.

0.05 – 0.19m Sandy mud with minor gravel. Dark brown (10YR4/3) becoming dark grey (10YR4/1) towards base. Poorly sorted, very soft with low plasticity. Sand very fine to very coarse with subangular to rounded quartz. Low percentage lithic grains and shell debris. Moderate reaction with HCl, becoming weaker towards base.

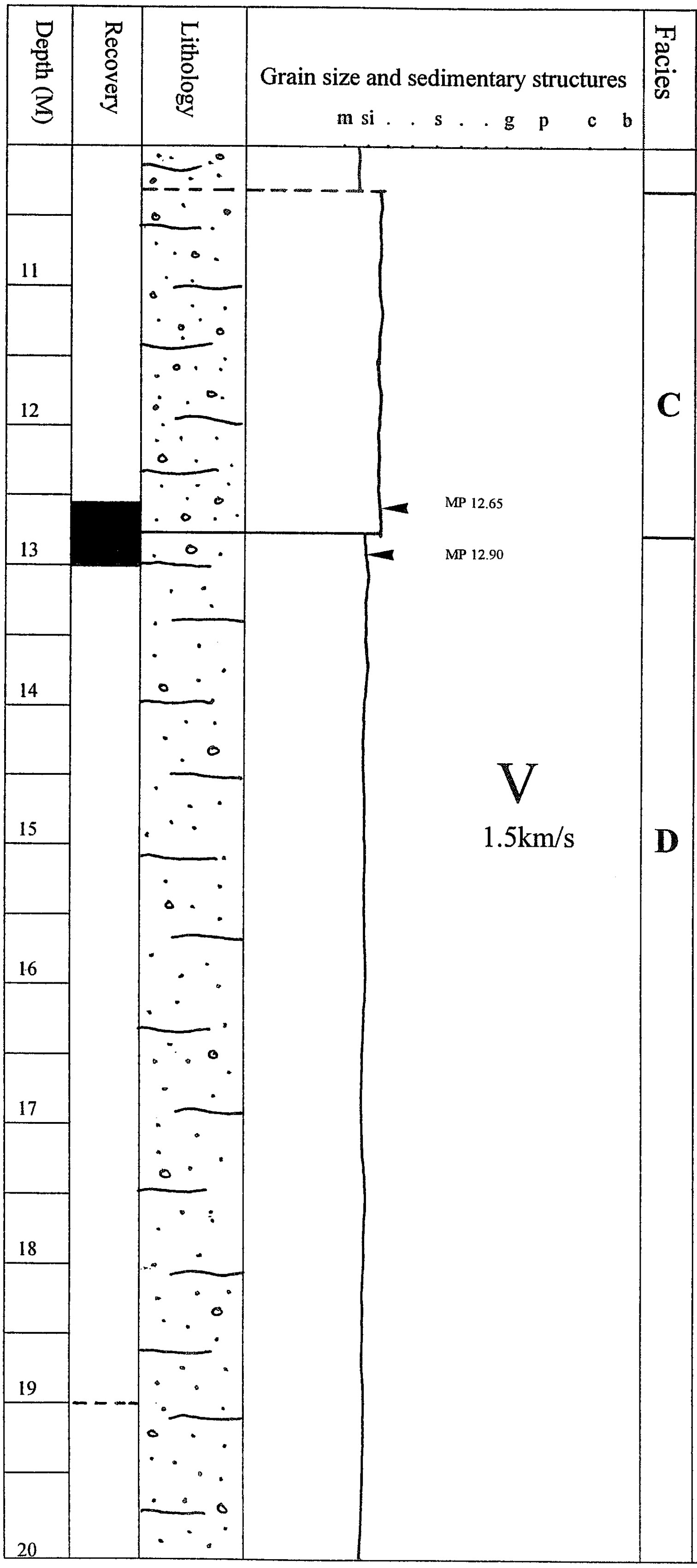
0.19 – 1.93m Mud with minor gravel. Dark grey-brown (10YR4/2). Very poorly sorted, very soft with intermediate plasticity. Minor percentage, very fine quartz-rich sand. Subrounded gravel with a clast size up to 20mm. clast lithologies include various metamorphics, red sandstone and basalt. Weak reaction with HCl.

0.93m	Shear strength	4.4 KPa
	Compressive strength	5.7 KPa
1.93m	Shear strength	6.4 KPa
	Compressive strength	8.3 KPa

7.20 – 8.00m Sandy Mud. Brown (7.5YR4/2). Approx 70% mud 20 – 30% silt and fine to medium sand, with minor pebbles up to 30mm and shell debris. Sand dominantly quartz with subangular to subrounded grains. Pebbles composed of siltstone and other unidentified lithologies. Band of coarse shell debris, mostly mollusc shell, at 7.34m. No reaction with HCl.

7.70m	Shear strength	6.0 KPa
	Compressive strength	5.36 KPa
	Water content	23.56%

Scale 1:50



Description

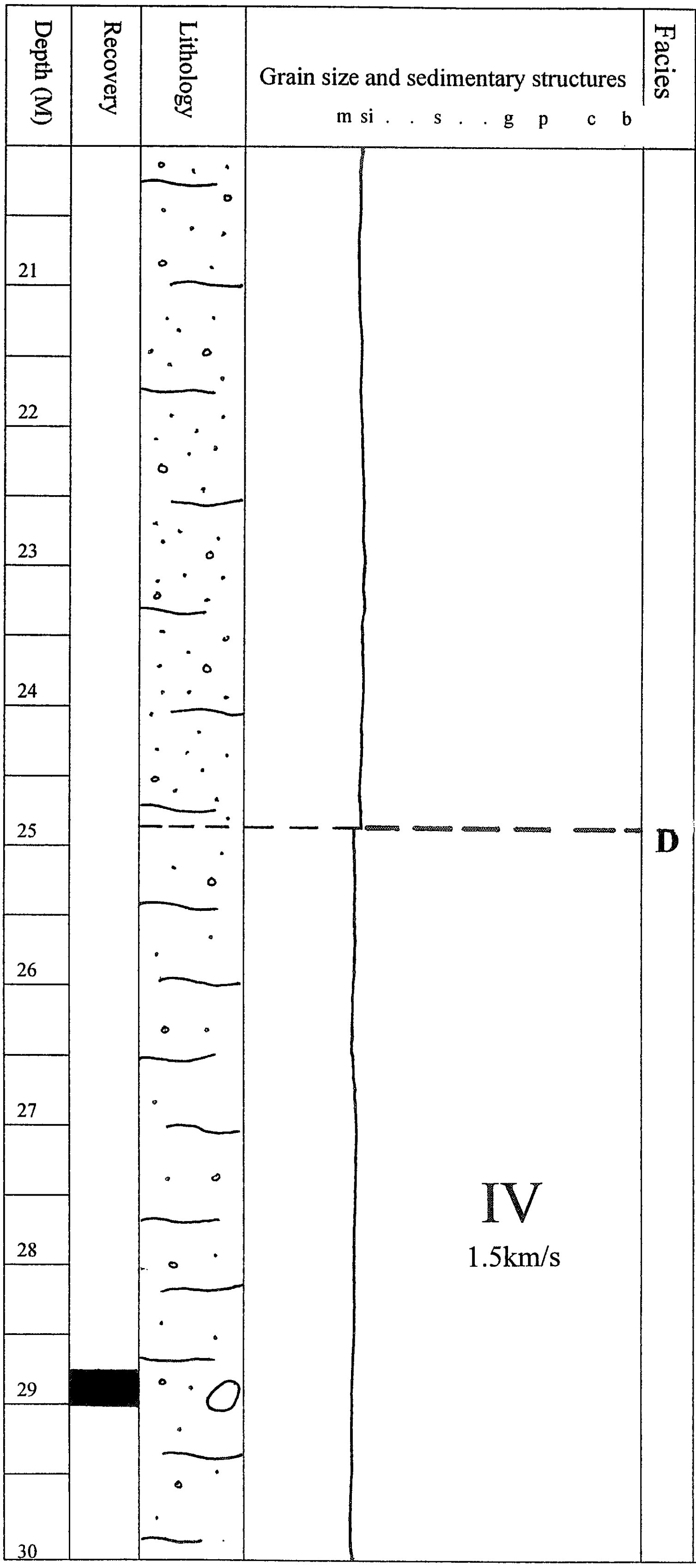
12.63 – 12.72m Sandy mud with minor gravel. Brown (7.5YR4/2). Soft and plastic. Poorly sorted with approx 60% mud, 35% fine to coarse sand and 5% pebbles and shell debris. Sand approx. 50:50 subangular to rounded quartz : lithic grains. Pebbles up to 20mm, mollusc fragments up to 50mm. Too disturbed for geotechnical tests.

12.72 – 13.00m Sandy mud. Similar composition to 7.20 – 8.00m. Rare shell fragments up to 20mm. Rare pebbles up to 10mm.

12.85m	Shear strength	16.0 KPa
	Compressive strength	25.0 KPa
	Water content	16.08%

19.00 – 23.00m Very poor recovery. Small fragments of mud similar to the above unit with pebbles up to 20mm.

Scale 1:50



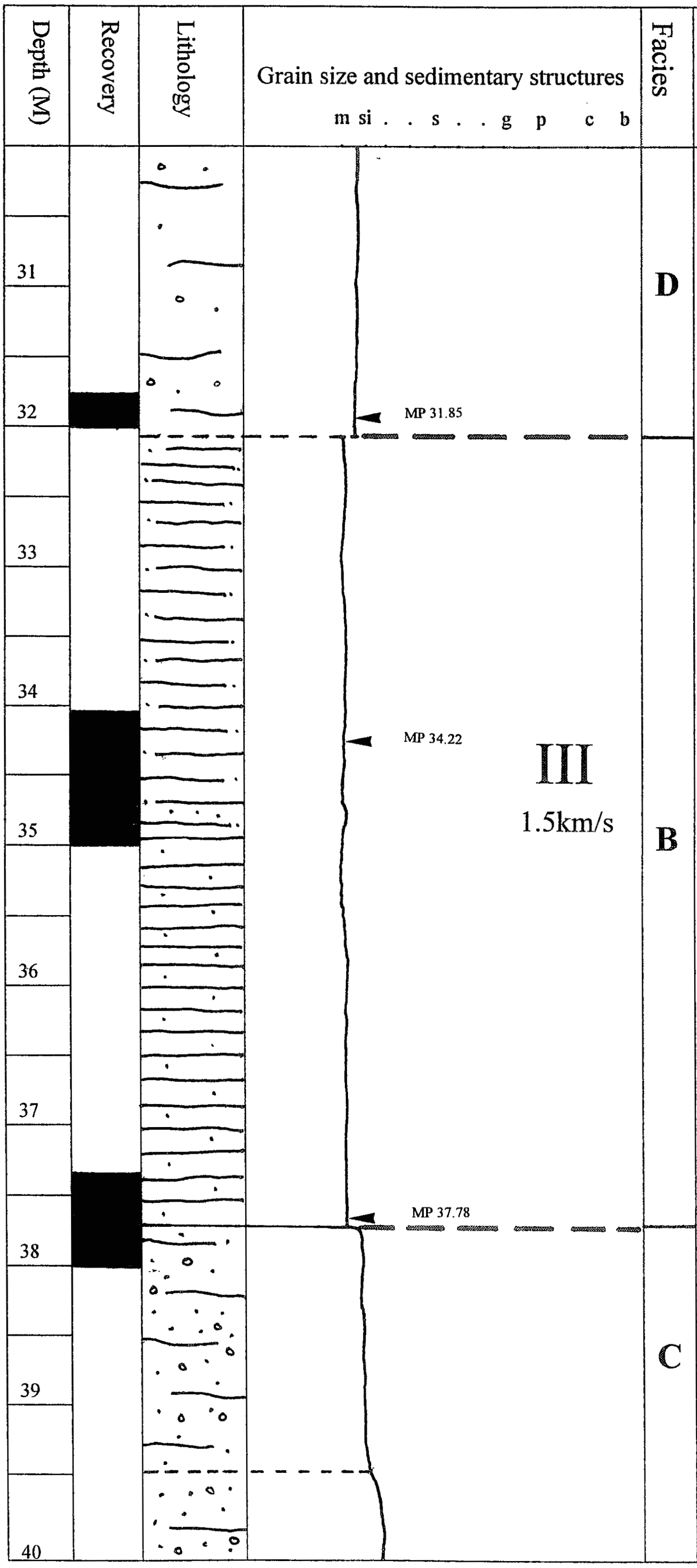
Description

19.00 – 23.00m Very poor recovery. Small fragments of mud similar to the above unit with pebbles up to 20mm.

28.76 – 29.00m Sandy mud. Dark green-grey (10Y3/1), plastic. ~80:20 Mud : sand. Sand fine to coarse, subangular to rounded, predominantly quartz. Rare pebbles up to 10mm. Small subangular amphibolite cobble (110mm) at base. Cobble has manganese coating on surface and remains of calcareous encrustation. Mud gives moderate reaction with HCl.

28.80m	Shear strength	30 KPa
	Compressive strength	60 KPa
	Water content	21.51%

Scale 1:50



Description

31.78 – 32.00m Sandy mud. As above. Small cobble (90mm) of red micaceous sandstone at base.

34.10 – 34.70m Sandy mud. Dark green-grey (10Y3/1). Approx 80:20 mud : sand. Sand fraction fine to medium grained , 75:25 quartz : lithics. Quartz grains subangular to rounded. Rare pebbles up to 5mm (< 1%) Abundant foraminifera and bivalve remains, including some complete valves. Strong reaction with HCl.

34.44m	shear strength	23.0 KPa
	Compressive strength	42.5 KPa
	Water content	24.42%

34.70 – 34.90m Sandy mud. Dark red-brown (5YR3/3). Plastic. ~ 75:25 mud : sand/silt. Sand fraction fine to medium sand, 60:40 quartz : lithics, quartz grains subangular to rounded. Moderate reaction with HCl.

34.78m	Shear strength	26.0 KPa
	Compressive strength	52.5 KPa

34.90 – 35.00m Sandy mud. Very dark grey-brown (10YR3/2), changes to a reddish brown after prolonged exposure. 70:30 mud : fine sand/silt. Sand fraction approx 70:30 quartz : lithics. Most quartz grains are Fe stained. Strong reaction with HCl. Too disturbed for geotechnical tests.

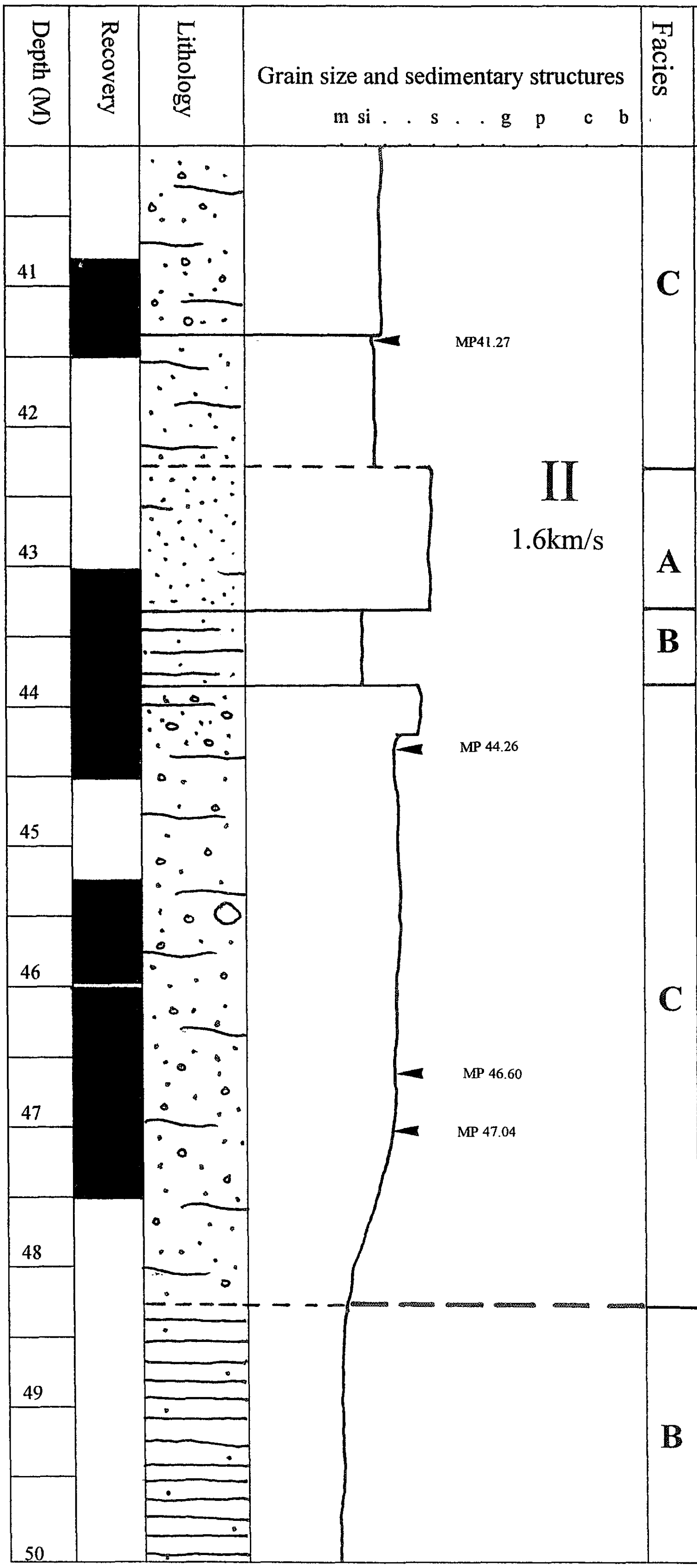
37.40 – 37.79m Silty mud. Very dark grey-brown (2.5Y3/2). Plastic. 75-85% mud, 5-10% fine to medium quartz-rich sand, 10-15% silt. Quartz grains subangular to subrouned. Moderate reaction with HCl.

37.70m	Shear strength	30.0 KPa
	Compressive strength	31.25 KPa
	Water content	25.73%

37.79 – 38.00m Sandy mud. Dark red-brown (5YR3/3). Approx 55% mud, 15% fine sand and 30% silt.Small percentage lithic grains, mostly mica and silstone. Quartz grains Subangular to rounded, mostly Fe stained. Rare small pebbles up to 15mm below 37.91m.

37.90m	Shear strength	30.0 KPa
	Compressive strength	55.0 KPa

Scale 1:50



Description

40.82 – 41.42m Sandy mud with pebbles (diamicton), very poorly sorted. Dark red-brown (5YR3/3). Approx 55% mud, 45% silt to medium sand, 5% granules and small pebbles. Sand fraction 65:35, quartz : lithics. Quartz grains angular to rounded with many Fe stained grains. Pebbles up to 30mm, lithologies include dolomitic limestone, micaceous siltstone, quartzite, red siltstone and red sandstone. Matrix gives strong reaction with HCl.

41.04m	Shear strength	26.0 KPa
	Compressive strength	35.0 KPa
	Water content	17.15%

41.42 – 41.50m Sandy mud. Dark red-brown (5YR3/3). As above, but lacks pebbles.

43.02 – 43.31m Muddy sand. Dark red-brown (5YR3/3). Unconsolidated sand with < 10% mud. Poorly sorted sand, very fine to very coarse with small percentage of granules. 75:25 quartz : lithics, quartz grains angular to rounded, many with Fe oxide coating. Lithic grains include limestones, red sandstones, gneiss, amphibolite, micas and possible basalts. Weak reaction with HCl.

43.20m	Shear strength	26.0 KPa
	Compressive strength	125.0 KPa
	Water content	15.03%

Sand unit is re-worked/homogenised from drilling.

43.31 – 43.84m Sandy mud (Diamicton). Dark red-brown (5YR3/3). Approx 20-30% very fine to medium sand. 90:10 Quartz : lithics. Quartz grains saubangular to rounded, many with Fe oxide coating. Rare, (< 1%) small pebbles up to 10mm. Strong reaction with HCl.

43.54m	Shear strength	15.0 KPa
	Compressive strength	15.0 KPa

43.84 – 44.17m Gravelly sandy mud (Diamicton). Dark red-brown (5YR3/3). Very poorly sorted, approx. 50% mud, 30-40% silt and fine to coarse sand, 10-20% large granules and small pebbles. Pebbles up to 15mm. Sand fraction, 80:20 quartz : lithics, Quartz grains angular to rounded, larger grains generally more rounded than finer grains. Many quartz grains with Fe oxide coating. Lithic grains include limestone, red sandstone red siltstone, yellow sandstone and gneiss. Lithic grains subangular to subrounded. Matrix gives strong reaction with HCl.

44.03m	Shear strength	22.0 KPa
	Compressive strength	18.0 KPa
	Water content	15.77%

44.17 – 44.50m Sandy mud with pebbles (Diamicton). Approx 65% mud, 35% sand and silt, 1-3% pebbles. Sand fraction mostly fine sand, range from very fine to granules. 85:15 quartz : lithics, quartz grains subangular to rounded. Lithics include limestone, amphibolites sandstones, gneiss and possible basalts. Matrix gives strong reaction with HCl.

44.37m	Shear strength	26.0 KPa
	Compressive strength	31.25 KPa
	Water content	17.19%

45.24 – 46.70m As above. Gneiss cobble (80mm) at 45.45m

45.62m	Shear strength	15.0 KPa
	Compressive strength	13.0 KPa
	Water content	18.94%
46.20m	Shear strength	18.0 KPa
	Compressive strength	15.0 KPa
46.60m	Shear strength	12.0 KPa
	Compressive strength	17.5 KPa
	Water content	18.92%

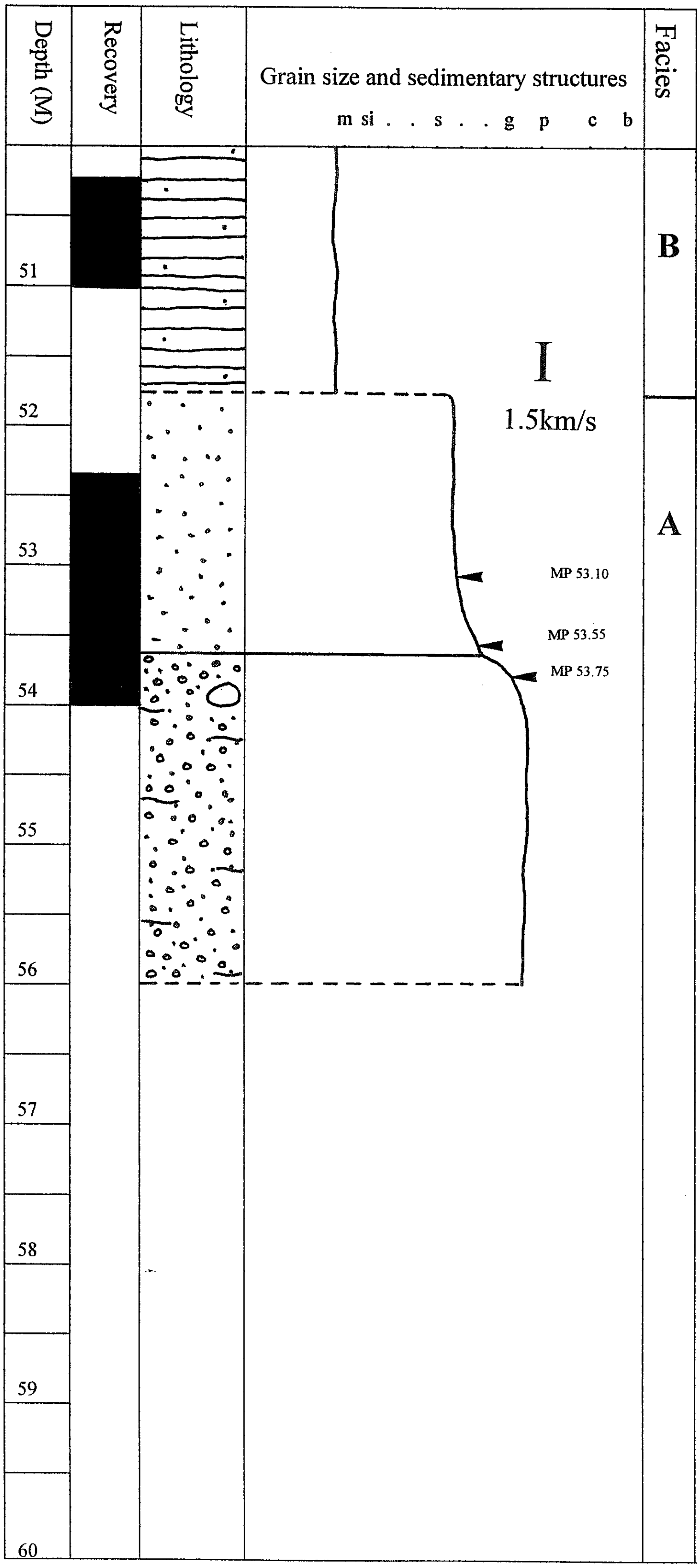
46.70 – 47.50m Silty mud, coarsening upwards to sandy mud/diamicton. Very dark grey-brown (2.5Y3/2) at base with gradational change upwards to dark red-brown (5YR3/3). Base approx 80:20 mud : silt. sand fraction is < 1%. Sand and pebble content increase upwards.

47.30m	Shear strength	31.0 KPa
	Compressive strength	25.0 KPa
	Water content	29.87%

Borehole 99/3

Sheet No. 6 of 6

Scale 1:50



Description

50.22 – 51.00m Mud/silty mud. Very dark grey-brown (2.5Y3/2). 95+% mud and silt, sand <5%. sand fraction very fine to medium, 70:30 quartz : lithics. Quartz grains subangular to subrounded with some Fe oxide coating. Moderate reaction with HCl.

50.30m	Shear strength	23.0 KPa
	Compressive strength	21.0 KPa
	Water content	30.53%

Unit shows evidence of disturbance and drying.

52.38 – 53.66m Sand. Unconsolidated, medium to very coarse, granular to medium near base, fines upwards. mud matrix < 5% at top , < 2% at base. 70:30 quartz : lithics, proportion of lithics increases towards base, lithic grains generally coarser grain size. quartz grains angular to well rounded, Approx 35% of quartz grains are Fe oxide coated/stained and are more angular. Lithic grains include limestone, red and green sandstones, basalt, gneiss, amphibolites and garnet. Foraminifera abundant in some levels, rare or absent in others.

53.66 – 54.00m Muddy gravel. Dark green-grey (10Y4/1). Approx 60% gravel 40% sandy mud matrix, matrix 30:70 sand : mud. matrix decreases towards base. Sand fraction 60:40 quartz : lithics. quartz, subangular to rounded, lithics include limestone, sandstones, gneiss, basalts. Small basalt cobble (110mm) at base. Matrix gives weak reaction with HCl.

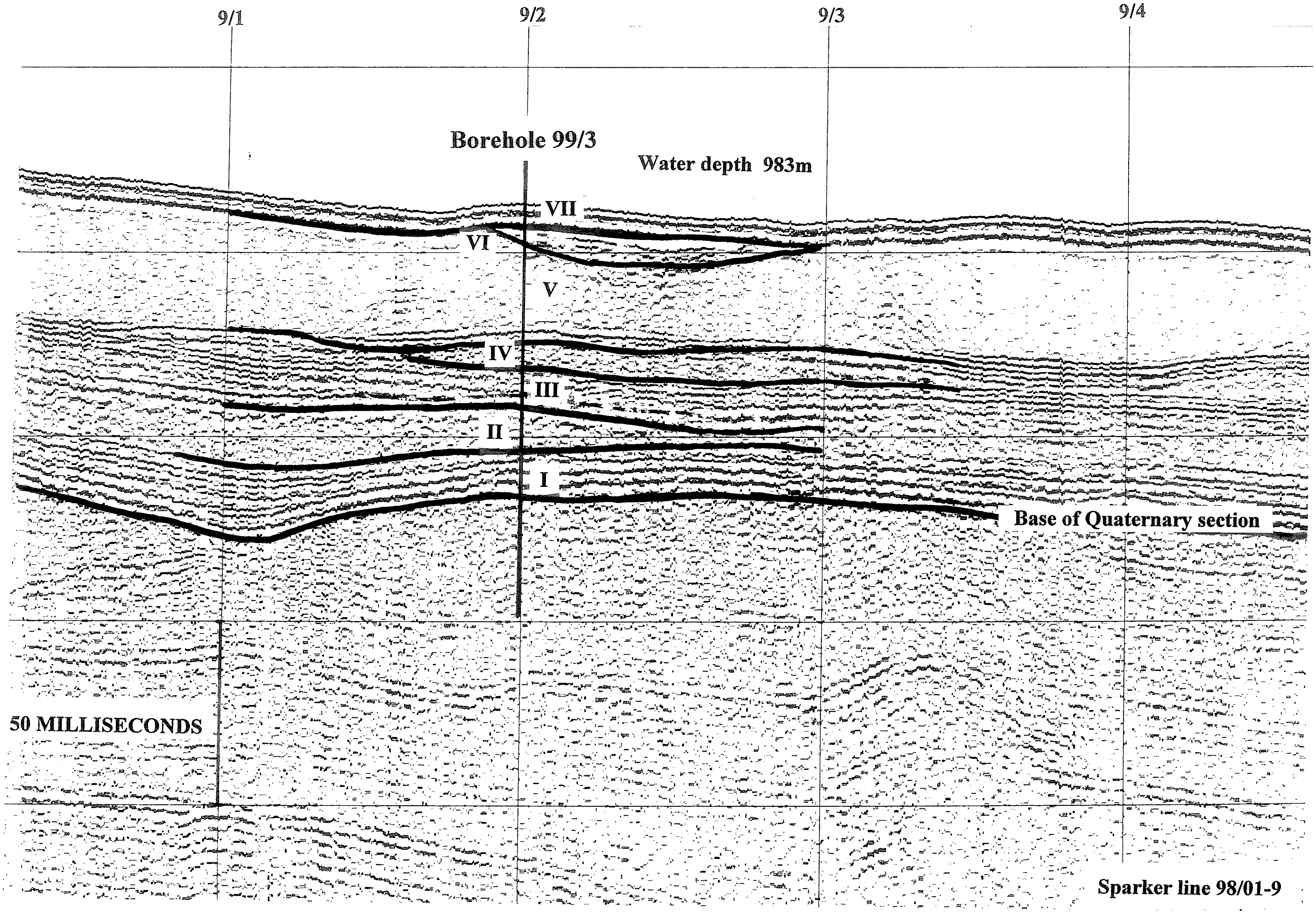


Figure 5. Interpretation of seismic data from area of borehole 99/3

4.1 Interpretation of borehole 99/3

The sparker data from a seismic survey of the area around borehole 99/3 shows a sequence of 7 reflector packages alternating between thin parallel to sub-parallel packages and thicker chaotic to isotropic units(figures 4a & b and 5). The base of the Quaternary is defined from this data as being approx. 56m below the seabed (Hitchen, 1999) using an average velocity of 1.5 km/s. This depth unfortunately corresponds to an interval of no core recovery and consequently a definitive lithological horizon cannot be identified. Broadly, the seismic packages correlate well with the main lithological facies associations and enables the fixing of some of the boundaries between lithologies within intervals of no core recovery.

4.1.1 Package I

The lowermost seismic unit, package I, shows a thin sequence of acoustically stratified reflectors above the basal unconformity of the Quaternary. These reflectors correspond to the sands of facies A and muds of facies B. The inclusion of cold water Pleistocene foraminifera within the basal facies A unit (see micropalaeontology section) indicates that glacial conditions were already established in the source region of these sediments and that the pre-glacial Quaternary Succession has either been re-worked and removed, or was never deposited. A re-worked assemblage of palynomorphs was also recorded from the basal facies A sands which included numerous Cretaceous spores and dinoflagelates.

The coarse sand and gravel unit at the base of the Quaternary section is probably a combination of facies A sands and a lag deposit of pre-glacial material. The age of deposition of the lag deposit component is not known, but may represent a significant break in deposition. There are two broad possibilities for the origin of the package I facies A sands; deposition by contour currents or deposition by downslope currents. Deposition and re-working by downslope bottom currents is favoured by the sparker data from line 98/01-9 which lies parallel to the strike of the slope (figure 5). The borehole position at fixed point 9/2 shows the basal section is composed of parallel reflectors. However, further southwest at fixed point 9/1 there are a series of discontinuous draped reflectors which partly infill the topography of the Quaternary unconformity. This suggests the currents may have been partly channelised. If contour currents flowing parallel to the strike had been responsible, the infill of this topography might be expected to have a more sigmoidal character. Deposition from the downslope currents may have initiated the fan-like morphology seen at the base of the continental slope on the present day seabed image (Figure 2). The overlying facies B muds of package I also contain a cold water foraminifera assemblage, which is consistent with this facies being the product of deposition from suspension of sediment from meltwater input and from distal ice rafting processes. The Fe oxide coated quartz grains from within these muds are unlikely to be locally derived and are probably transported from the shelf or even onshore red-bed sediments.

4.1.2 Package II

The sediments at the base of seismic package II are transitional with those of the underlying group. The initial coarsening upwards nature of the facies C diamictons in this package suggests the onset of significant input of ice-rafted debris, prior to the deposition of the bulk of the unit. The seismic character of this package is one of a lobe-shaped body with isotropic to chaotic reflectors. This type of seismic signature is typical of massive diamicton bodies deposited as tills or debris flows. An increased average velocity for this package of 1.6km/s was used in the correlation with the core on the grounds of a noted increase in density (see section 2.3). Given the shape of this package, and its position near the base of the slope, deposition by a debris flow event is the most likely scenario. The arctic faunal assemblage and the polymict nature of the pebble suite suggests that these sediments were derived from glacial material originally deposited as ice-rafted debris or a till delta further up the slope.

Within package II there are two brief changes in lithology between 43.84m and 43.02m, firstly to facies B muds and then to facies A sands, before reverting to the facies C diamicton. This change is not detectable on the seismic image but may represent a period of slope stability during which only background glaciomarine deposition from icebergs and meltwater delivered sediment to this locality. Following the accumulation of the muds, a further thin unit of facies A sands was formed. The red-brown nature of these sands suggest formation by re-working of the underlying muds and diamictons by downslope currents which were possibly similar to those which formed the base of package I.

As accumulation continued upslope, instability caused a further debris flow resulting in the deposition of the second facies C diamicton. The relative coarseness of the facies C diamictons compared to those of facies D, suggests that the ice from which they originated was more proximal and may have reached the shelf edge.

4.1.3 Package III

Package III is a thin acoustically stratified group of reflectors above the debris flows of package II. This is represented in the core by approximately 6m of facies B silty muds using a velocity of 1.5km/s. It seems likely that this package resulted from a temporary return to a stable slope where fine grained glaciomarine sediment was the main input. The generally fine grained nature of the sediments in this package suggests that these represent distal glaciomarine deposition, the parent ice mass having retreated from the shelf edge. The core interval 34.90 – 34.10m, which corresponds to the upper section of package III, shows an increase in the coarse sediment component. This suggests the onset of a glacial re-advance, causing a consequent increase in the ice-rafted sediment input.

4.1.4 Package IV

Package IV is similar in origin to Package II. Acoustically it has the same characteristics of a lobe shaped body with weak to chaotic reflectors. It seems likely that package IV is of a debris flow origin similar to package II. The sediments forming package IV are muddy diamictons of facies D. The higher mud content in these sediments than the diamictons of package II suggests that the original sediments from which the package IV flow was derived also had a higher mud content.

The 3D architecture of the debris flow package shows a lateral variation in thickness, thinning both to the SW and NE, giving an overall elongated lobe shape. Line 99/01-10 (figure 4a) suggests the flow may have been confined on its NE side by an earlier debris flow deposit, confirming the stacked and coalesced debris lobes seen on the modern seabed image of figure 2.

4.1.5 Package V

The exact boundary between packages IV and V is difficult to identify in the core as it falls within an interval of poor recovery. However, applying an average velocity of 1.5km/s to the seismic data, the boundary lies at a depth of approximately 25m. The seismic image also suggests there may be a thin acoustically stratified package between IV and V. However, because of the lack of core recovery, this possibility cannot be confirmed.

Package V is of a different scale to the preceding units. It consists of a thick structureless body with few or no internal reflectors. It is also laterally persistent, varying little in thickness along slope and forming an elongated wedge on the downslope profile (figure 4b). These characteristics, combined with the nature of the facies D diamicton from which it is formed, indicate that this is a major debris flow. When the adjacent sparker survey lines, 98/01-8 and 98/01-10 are examined, it seems likely that package V could be an amalgamation of several large debris flows which are laterally extensive. These seismic lines also illustrate the considerable surface topography created by the flow lobes, with individual flows showing a topography of approximately 18m (using a velocity of 1.5km/s). This topography appears to be largely responsible for the present day surface morphology of the coalesced fans which form the slope apron observed on the seabed image (figure 2).

The thickness of these debris flows indicates there must have been a considerable build up of sediment higher up the slope or on the shelf break to provide sufficient source material. There are two possible causes for the magnitude of this build-up; i) sediment accumulation occurred over an extended periods distal glaciomarine deposits, with a relatively stable slope, ii) the ice front was near to, or reached the shelf edge and delivered large volumes of sediment directly to the slope in the form of a till delta and from ice-rafting. The second of these scenarios seems more likely as it would have produced a more rapid accumulation which is more likely to lead to slope instability.

The upper limit of package V is hard to define from the seismic image due to the presence of a smaller lobe shape unit of package VI which overlies the debris flow. The base of package VI is also marked by a series of poorly defined parallel reflectors. Using seismic velocities of between 1.5 and 1.5km/s the top of the V debris flow lies at a depth of between 7.5m and 10m. It is possible that the change from facies D to facies C at 12.72m may mark the end of the main flow, the remaining sediments making a return to proximal glaciomarine deposition. A concentration of shell debris occurs at 7.34m which would appear to mark a break in deposition and indicate current removal of fines. This horizon may also mark the upper boundary of package V.

4.1.6 Package VI

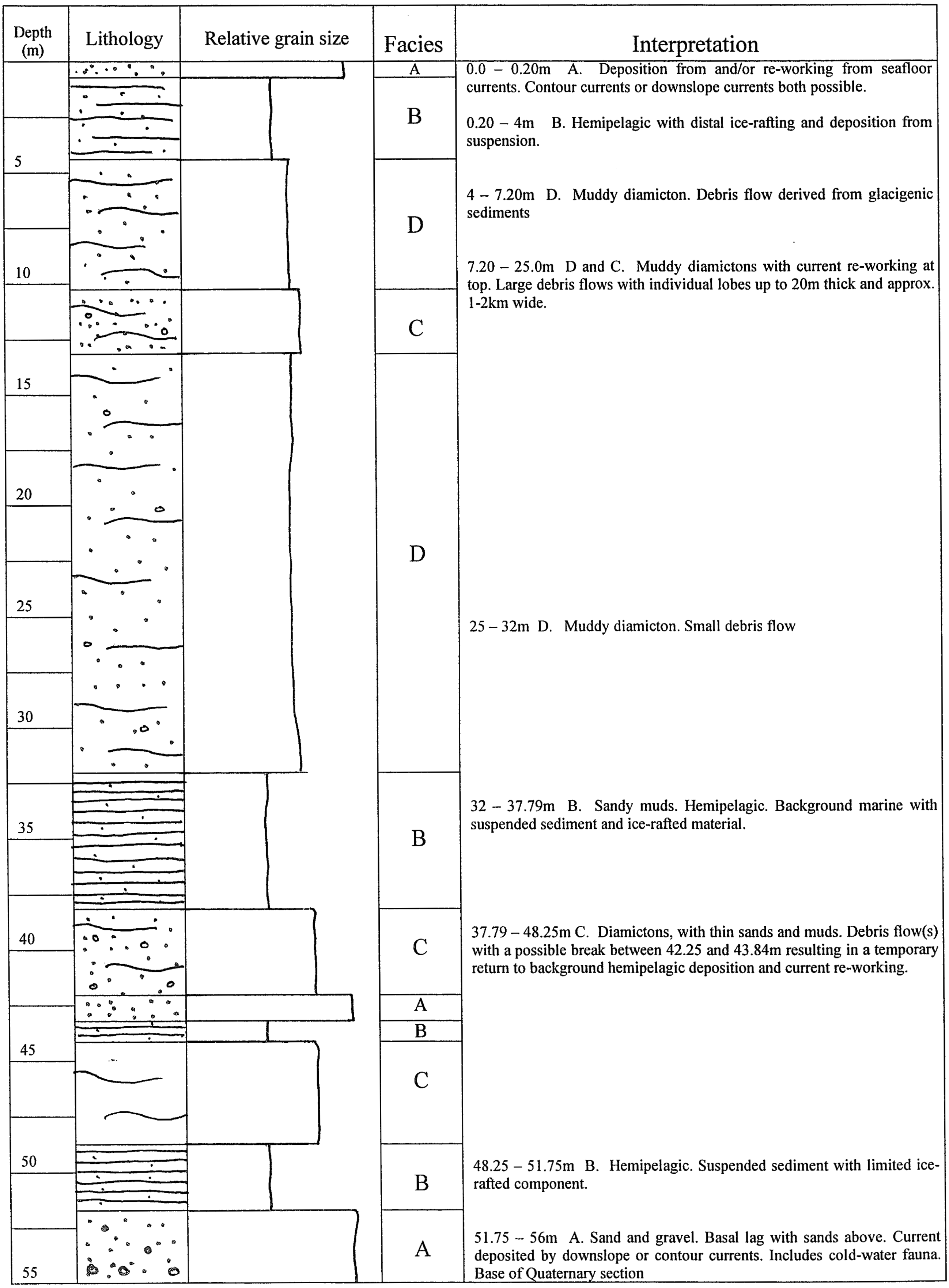
The seismic characteristics of package VI are similar to those of II and IV. This group is a thin structureless body with no internal reflectors and is composed of mud-rich diamictons from facies D. The package is laterally discontinuous but briefly thickens slightly to the NE. Downslope to the NW this package disappears, but does persist upslope to the SE and represents either a limited debris flow or the distal end of a larger flow. The sparker image from line 98/01-10 suggests that package VI is confined by the surface topography of the earlier larger lobes of package V.

4.1.7 Package VII

The final seismic package from the 99/3 borehole site shows a thin acoustically stratified group of parallel reflectors. The base of this group lies at a depth of approximately 4m to 5m and appears to form a moderately uniform thickness deposit over a large area.. The gravity core data from close to the borehole site (Fyfe and Egerton, 1998) suggests this package consists mainly of facies B sandy muds. The topmost 19cm are composed of sand and muddy sand of facies A but are too thin to show on the seismic image.

The facies B muds most likely represent a return to glaciomarine deposition with ice rafting, coinciding with the final retreat of glacial influence from this locality. The thin sandy facies A units at the top of this succession suggest current deposition and probable re-working of the surface of the underlying facies B muds.

Summary of lithologies and depositional processes for Borehole 99/3

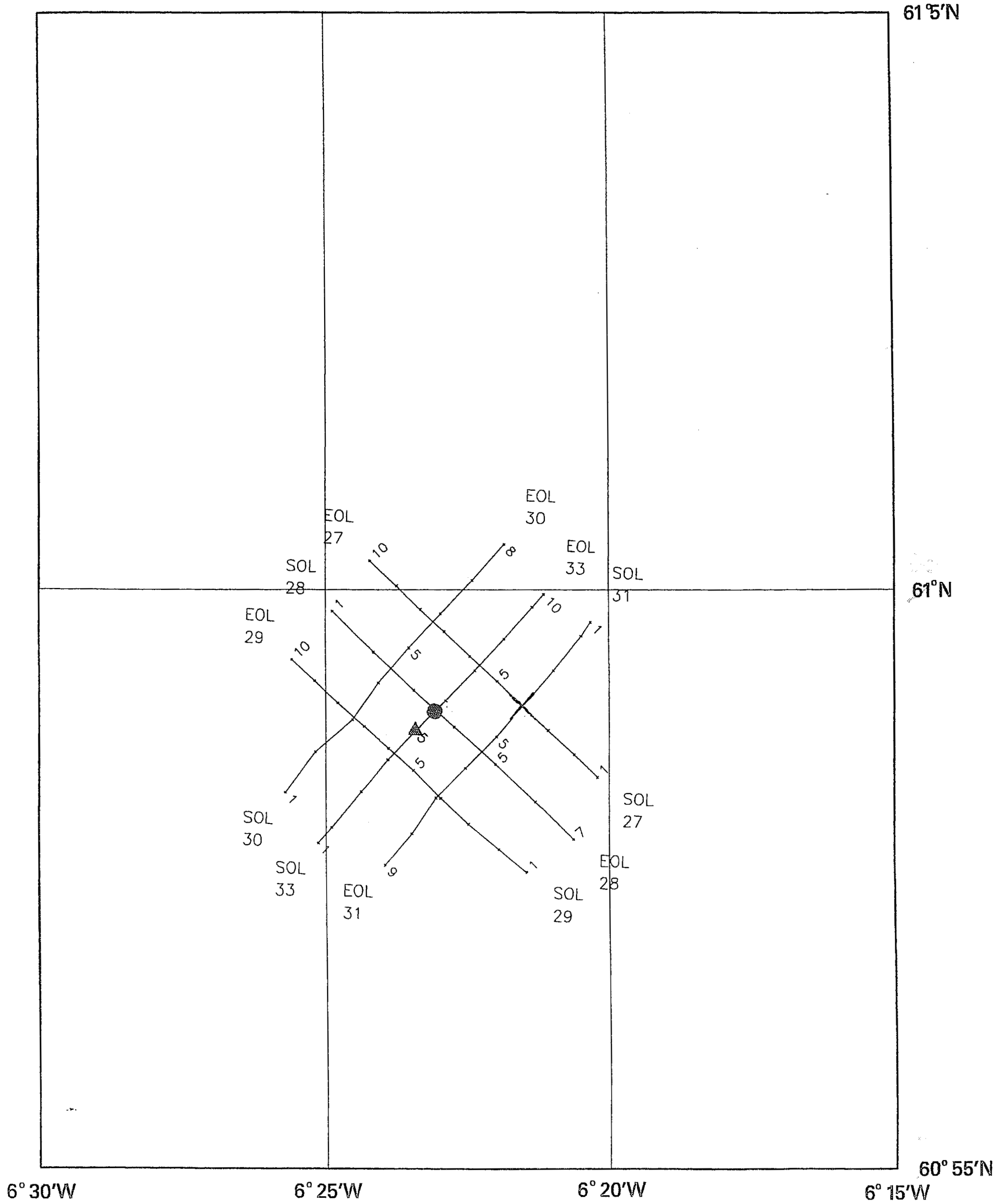


Borehole 99/4

Location:	Northern flank of Wyville-Thomson Ridge, c. 85km NW Cape Wrath
Latitude:	59° 58.778' N
Longitude:	06° 23.420' W
Map Area:	Sula Sgeir
Block Number	165/4
Date of drilling:	25-26th June 1999
Water Depth:	486m
Total depth:	16.85m
Depth to base of Quaternary:	c.15.17m

Gravity core No.	59-07/418
Latitude:	59° 58.96' N
Longitude:	06° 23.08' W
Date of sampling:	2nd June 1998
Water depth:	492m
Total depth:	0.43m

Figure 6. Location of sparker survey lines for borehole 99/4



● Location of gravity core (seabed sample)

▲ Location of borehole

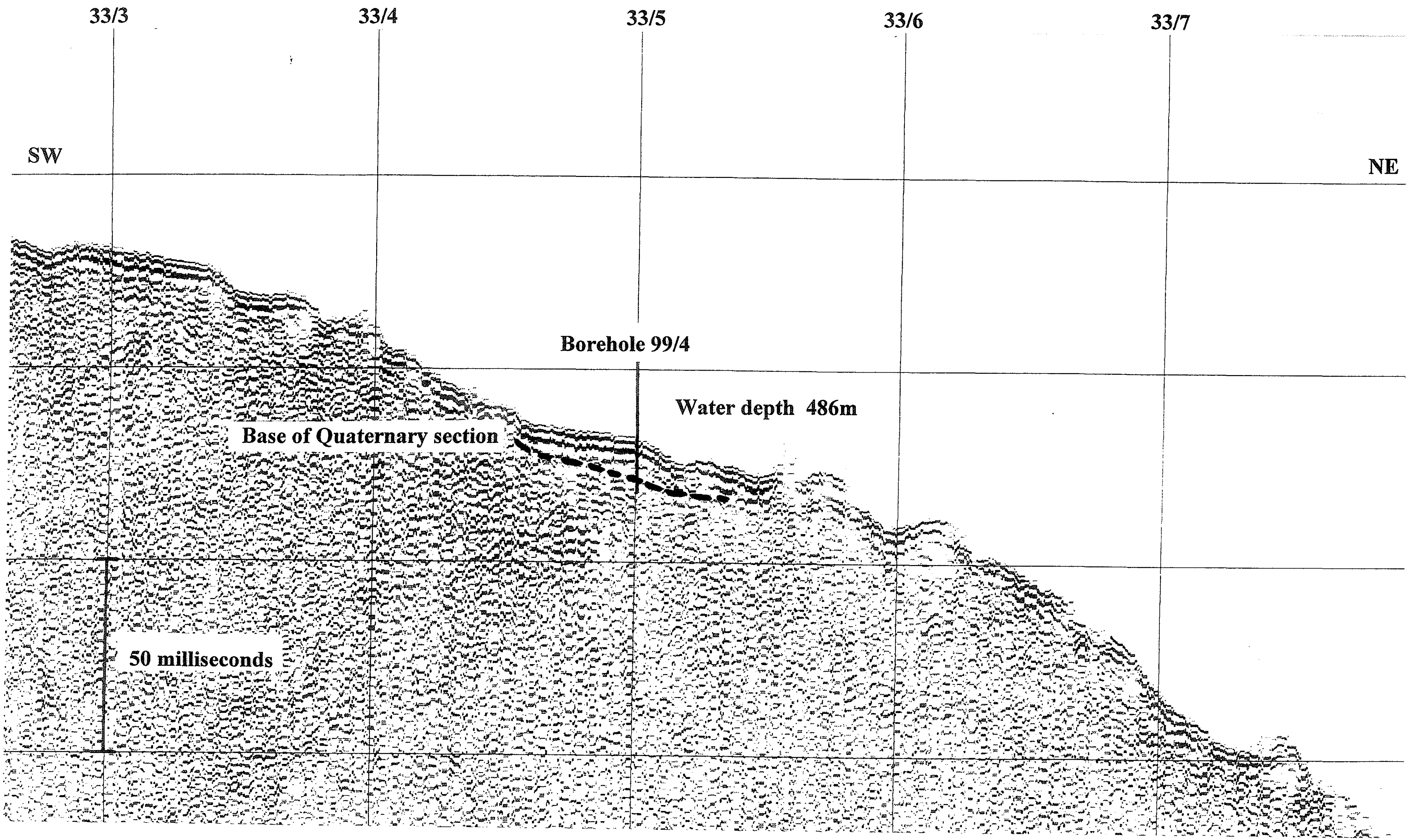
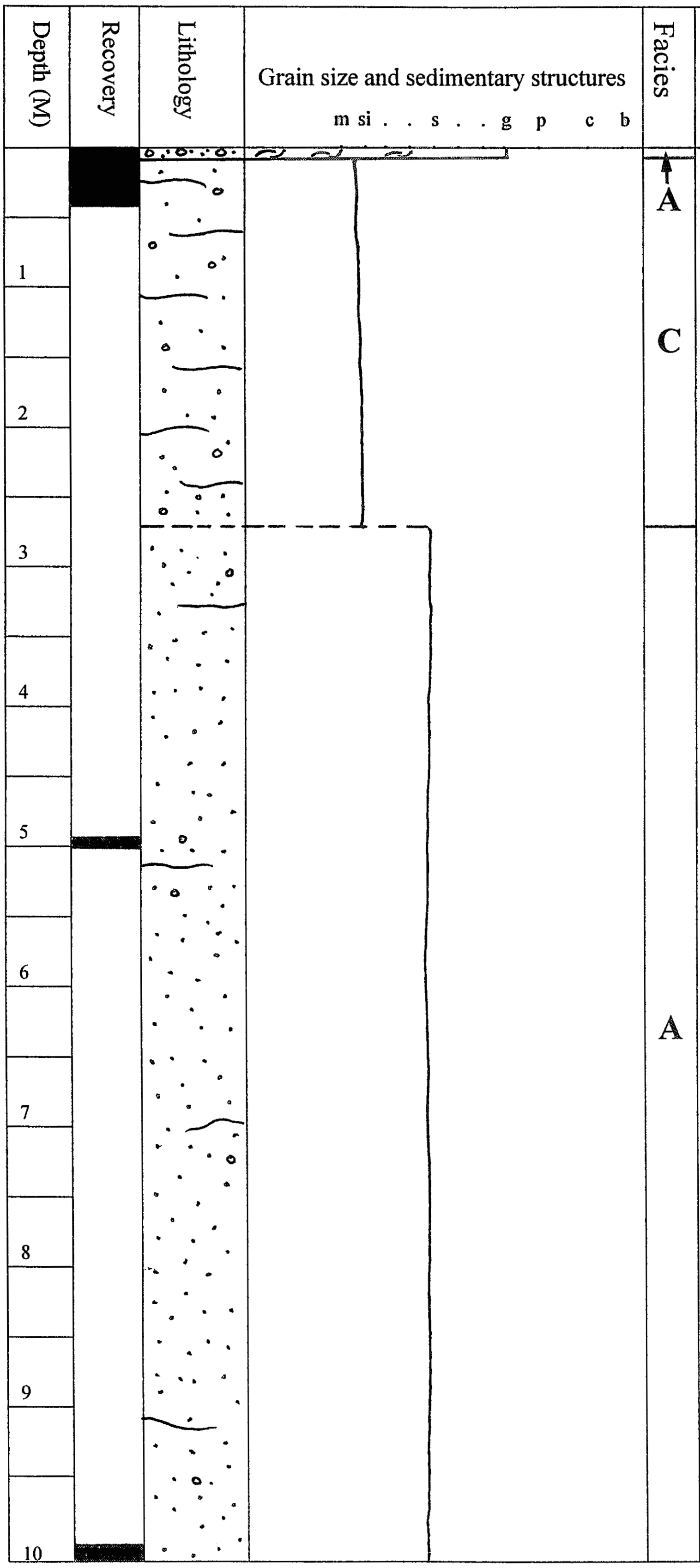


Figure 7. Seismic data from area of borehole 99/4. Line No. 98/01-33

Scale 1:50



Description

0.0 – 0.43m Gravity core data.

0.0 – 0.09m Sandy gravel. Dark yellow-brown (10YR4/4). Very poorly sorted, sand fine to very coarse with subrounded gravel, clast size up to 50mm, including basalt/amphiboloite encrusted with bryozoa and worm tubes. Quartz grains angular to rounded with 35% shell debris, including foraminifera, bivalve fragments, echinoid fragments and spines. Strong reaction with HCL. Sharp basal contact.

0.09 – 0.43m Slightly gravelly sandy mud. Pale brown (10YR6/3). Very poorly sorted, very soft with low plasticity. Sand fine to very coarse with subrounded gravel, clast size up to 10mm including red sandstones and basalts. Sand subangular to subrounded quartz and lithics. Approx. 5% shell debris, including large bivale and coral fragments. Moderate reaction with HCl.

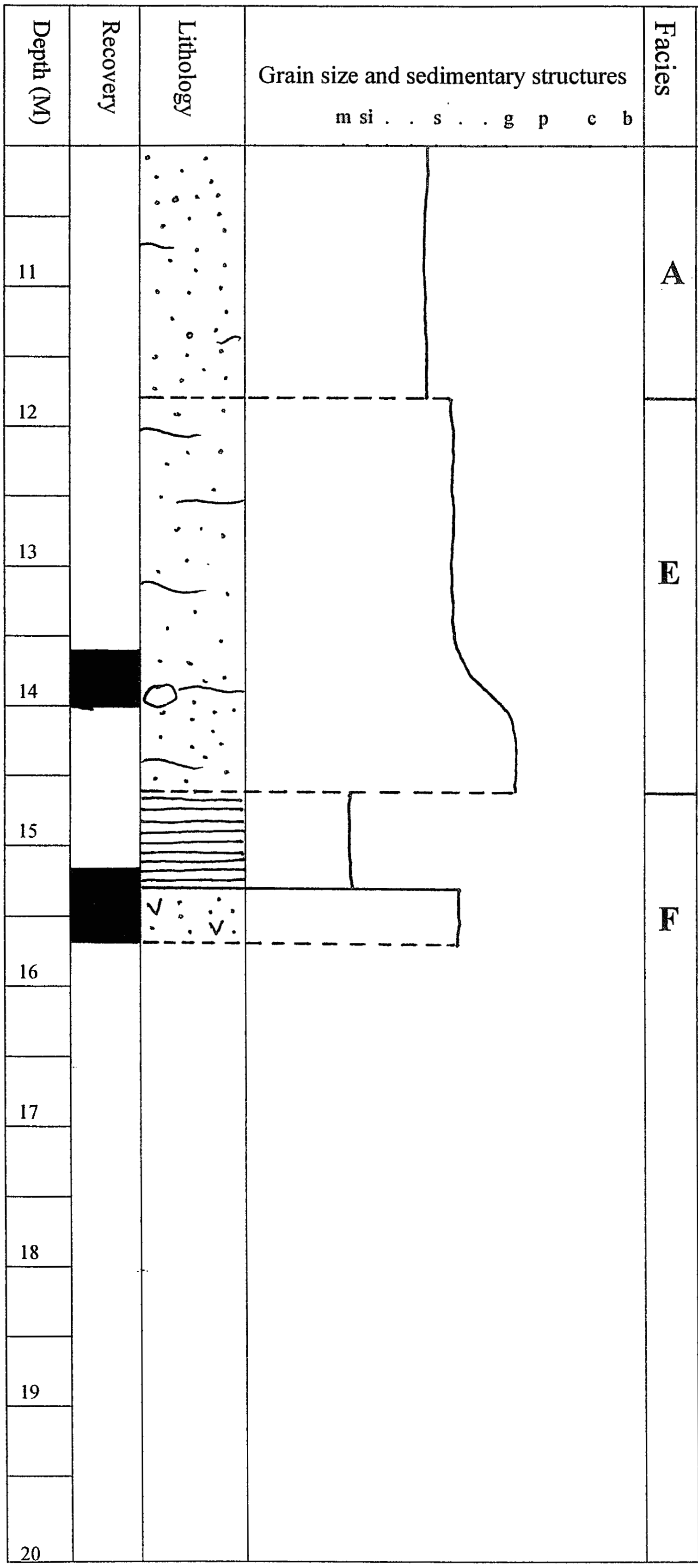
4.95 – 5.00m Muddy sand. Dark green-grey (5BG4/1). 30:70 mud : sand. Sand fraction approx 30% quartz, 70% lithics. Quartz grains very fine to fine, subangular to subrounded. Lithic grains mainly basalts medium sand to granule size. Rare basalt pebbles up to 20mm.

9.95 – 10.00m Very poor recovery. Small samples of muddy sand similar to above unit.

Borehole 99/4

Sheet No. 2 of 2

Scale 1:50



Description

13.62 – 14.00m Unconsolidated sand. Fines upwards from muddy granular sand at base, to muddy medium sand at top. Approx 75% sand, 20% mud. Sand composition, 50+% basalt grains, increasing downwards. Quartz grains angular to subangular. Common foraminifera and shell debris. Basalt cobble (100mm) at base.

15.17 – 15.30 Mud. Dark green-grey (5GY3/1). Plastic mud with basalt fragments. Very low percentage of quartz grains.

15.30 – 15.70+m Decayed basalts. Basalts in various states of degradation with amygdaloidal horizons.

4.2 Interpretation of Borehole 99/4

Very poor core recovery and poor seismic data make a detailed interpretation of 99/4 impossible. The base of the Quaternary lies between 14.0 and 15.17m. The base is composed of facies F basalts and muds which may be of Tertiary age. The presence of the basalt decay products appears to indicate that weathering was in-situ and that there was insufficient current activity to remove them. This is in sharp contrast to the overlying Quaternary deposits of facies A which are composed of unconsolidated muddy sands. In the interval 13.62-14.00m these sands show a fining upwards tendency suggesting evidence of current activity.

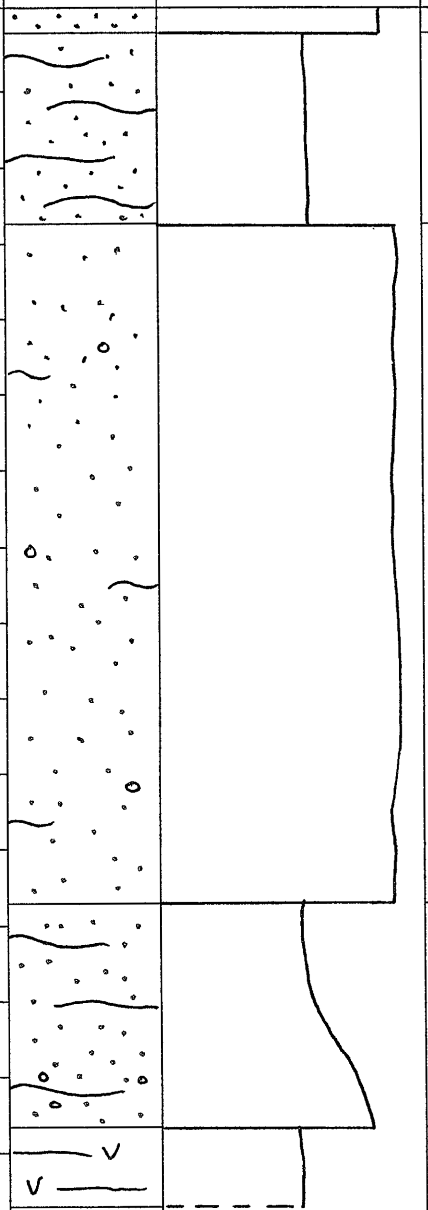
Samples from 10.00m and 13.86 were taken and analysed for foraminifera for a previous study (Hitchen, 1999). The results obtained from this earlier study showed abundant *Paromalina crassa*, which is normally an upper bathyal species (see micropalaeontology section, Appendix 1) and several arctic species, *Neogloboquadrina pachyderma* (sinstral), *Globigerina bulloides* and *Cassidulina reniforme*. The presence of the cold water fauna indicates that these sediments were either deposited under arctic conditions, or derived from glaciomarine sediments and later re-worked. The presence of deep water species suggests the inclusion of locally derived sediment is also a possibility.

The seismic images for the borehole area (figure 7) are a limited aid to interpretation of the borehole section. These show a thin series of reflectors with a poorly defined base and provide no clear indication of the depositional processes.

The upper section, derived from gravity core data, is composed of facies C diamicton, overlain by facies A sands. The diamicton may be the result of ice rafting, but the lack of stratification from the core suggests it could also be a flow deposit. The facies A sands at the top of the section are indicative of current activity which has probably re-worked the top of the underlying diamicton and may have brought in sediment from elsewhere.

Summary of lithologies and depositional processes for Borehole 99/4

Depth	Lithology	Relative grain size	Facies	Interpretation
0–0.09			A	0.0 – 0.09m A. Sandy gravel. current deposited and/or re-worked. Contour or downslope currents.
2			C	0.09 – 2.75m C. Sandy mud/diamicton. Probably a debris flow or muddy turbidite.
4, 6, 8, 10			A	2.75 – 11.75m A. Sands/muddy sands. Current deposited, possibly turbidites. Recovery too poor for accurate diagnosis.
12, 14			E	11.75 – 14.60m E. Muddy sands, fining upwards. Current deposited. Probably turbidite
16			F	14.60 – 15.70m F. Decayed basalts and derived clays. In situ.
18, 20				

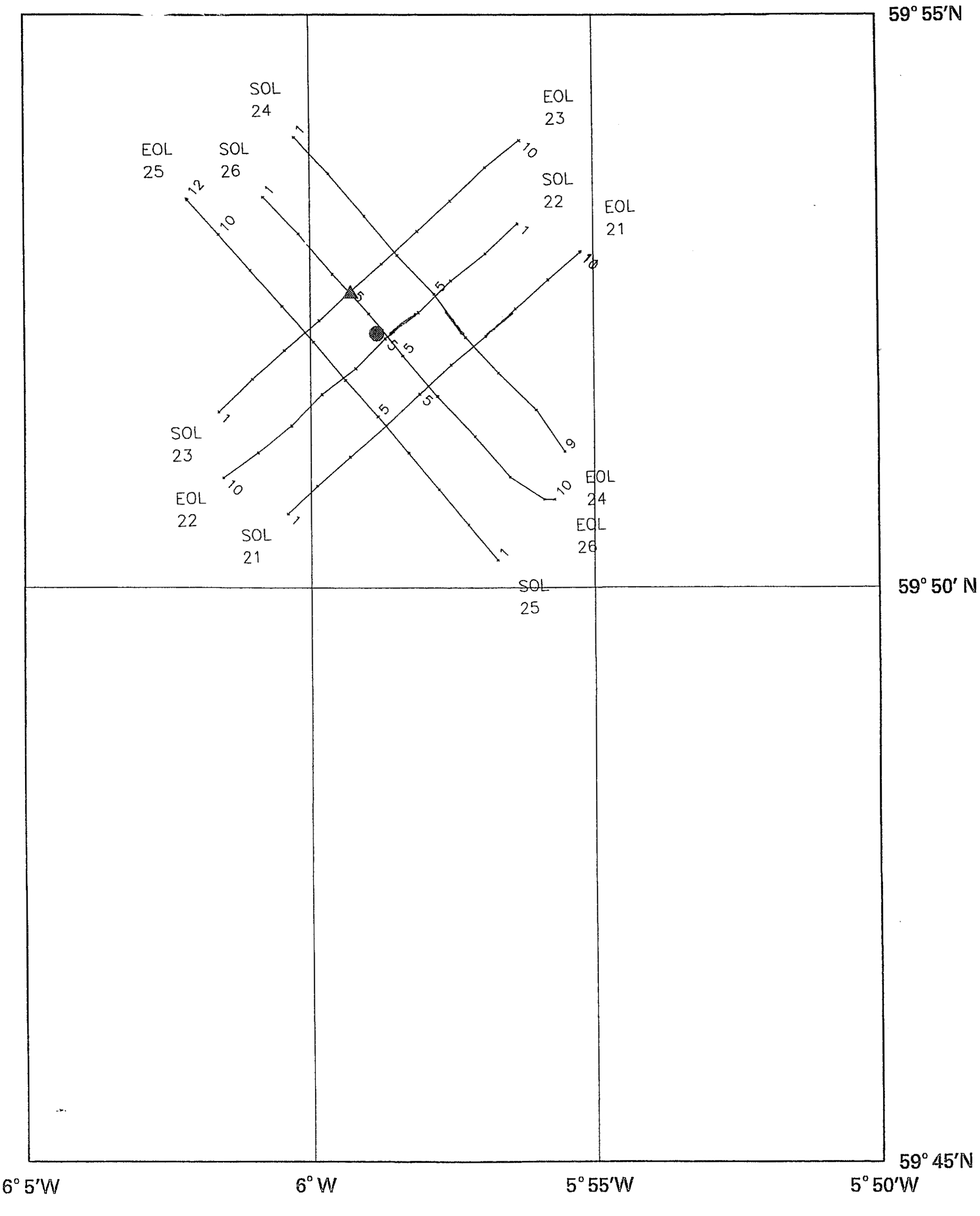


Borehole 99/5

Location:	Northern flank (SW end) of Wyville-Thomson Ridge, c. 75km NW of Cape Wrath
Latitude:	59° 52.553' N
Longitude:	05° 59.316' W
Map Area:	Rona
Block No.	166/1
Date of drilling:	26-27th June 1999
Water Depth:	705m
Total depth:	39m
Depth to base of Quaternary:	c.33.70m

Gravity core No.	59-06/384
Latitude:	59° 52.21'N
Longitude:	05° 58.84'W
Date of sampling:	2nd June 1998
Water depth:	605m
Total depth:	0.58m

Figure 8. Location of sparker survey lines for borehole 99/5



● Location of gravity core (seabed sample)

▲ Location of borehole

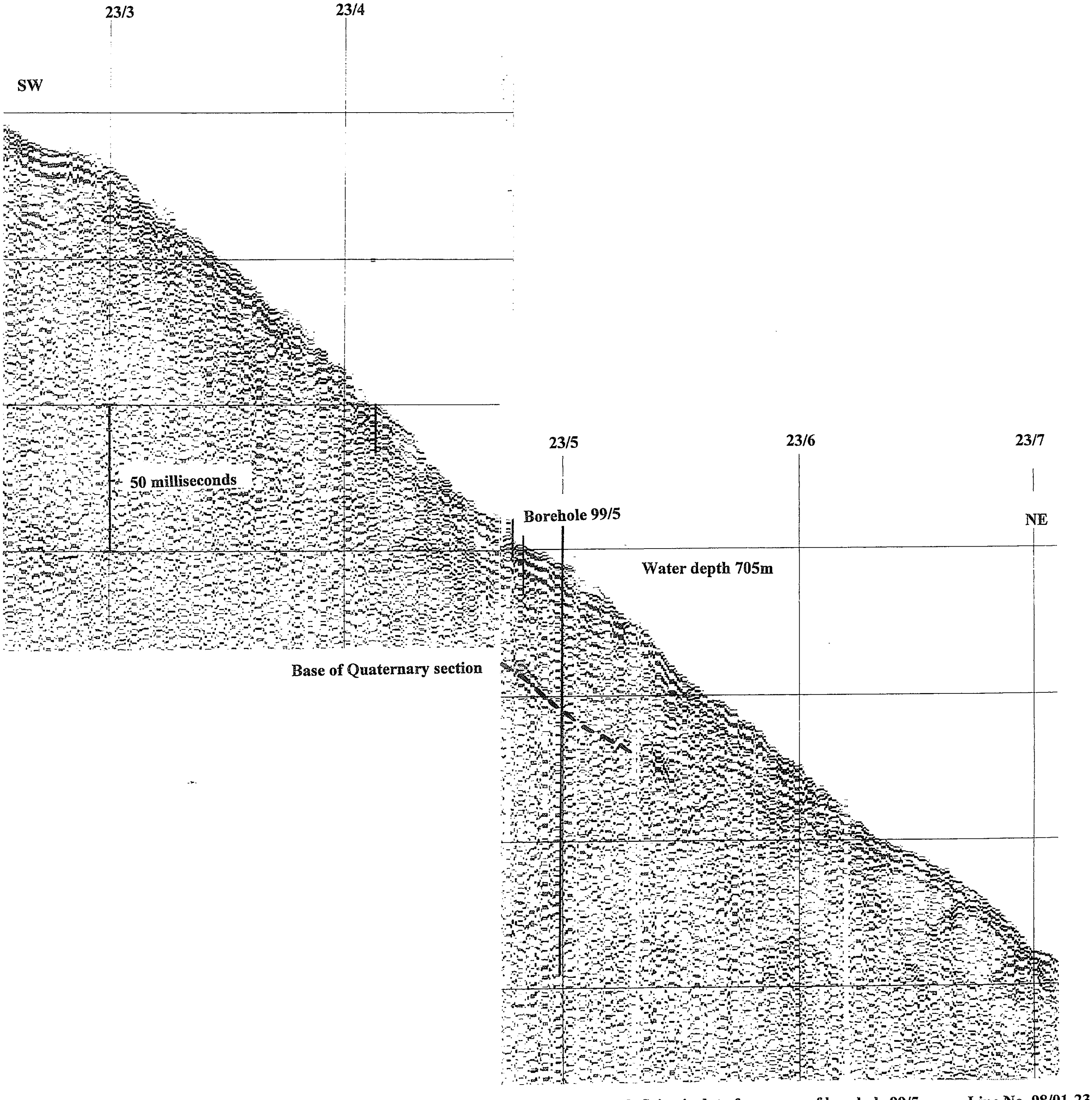


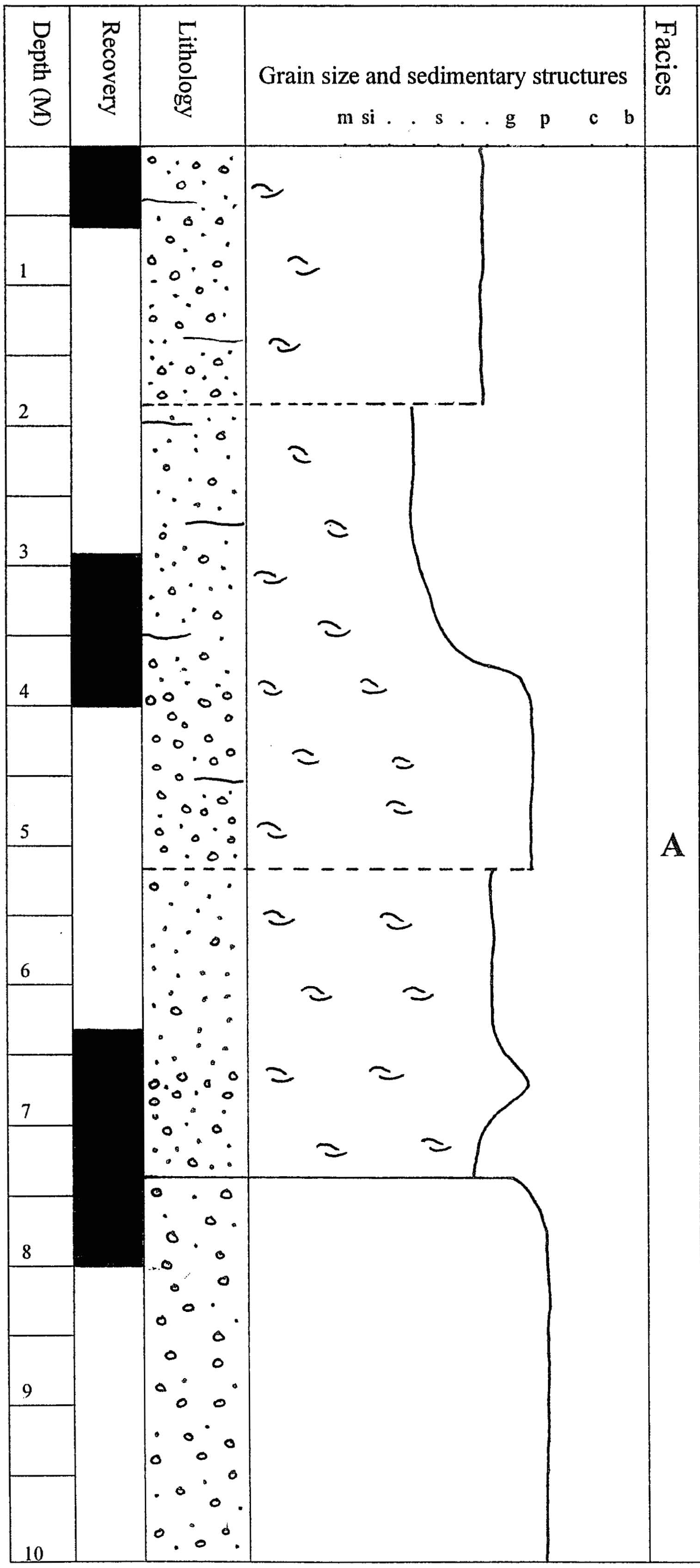
Figure 9. Seismic data from area of borehole 99/5.

Line No. 98/01-23

Borehole 99/5

Sheet No. 1 of 4

Scale 1:50



Description

0.0 – 0.58m Data from gravity core

0.0 – 0.58 Gravelly muddy sand. Vary dark grey-brown (2.5Y3/2). Very poorly sorted. Sand, very fine to very coarse with angular to subrounded grains. Gravel clasts up to 45mm, subangular to rounded. Lithologies include fine grained green sandstones, red sandstones, gneiss and amphibolite. Approx. 2% shell debris. Moderate reaction with HCl.

2.96 – 3.78m Muddy sand. Unconsolidated waterlogged sand. Fining upwards from coarse to granular sand with gravel at the base, to medium sand at the top. Approx. 60% quartz, 25% lithics and 15% shell debris at top. Mud and silt <5%. Quartz grains are angular to well rounded, larger grains being more rounded than finer fraction. Lithic grains include gneiss, amphibolite, limestone, mafics, basalt, epidote(?). Shell debris includes rare foraminifera, coral fragments, bivalves, gastropods, echinoid spines, serpulid worm tubes. Towards base, approx. 20-30% gravel, 50% granules and 20%+ sand and mud. 30:70 quartz : lithics, gravel clasts up to 5mm, subrounded to rounded. Shell debris up to 10% includes all of the above fauna and complete valves of bivalves.

3.10m	Shear strength	5.0 KPa
	Compressive strength	25.5 KPa
3.70m	Shear strength	5.0 KPa
	Compressive strength	22.5 KPa

Geotechnical results of questionable value due to probable reworking.

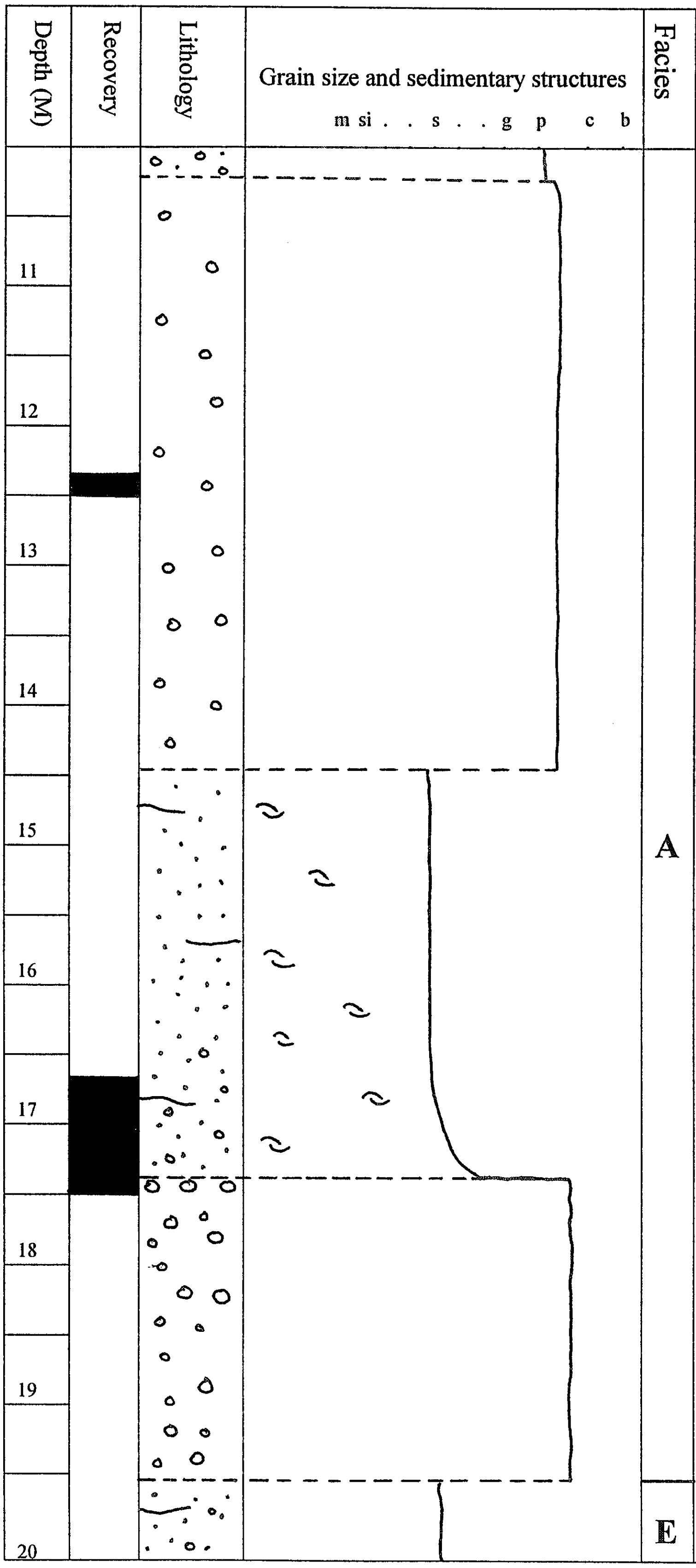
3.78 – 4.00m sandy gravel. Unconsolidated (reworked-?) gravel at base, fining upwards into coarse to granular sand at top. Gravel clasts 5 – 40mm, mostly rounded to well rounded, larger pebbles generally angular to subangular. Lithologies include gneiss, quartzite and sandstones. large fragments of shell debris up to 15mm, similar to those in the above unit. Basal gravel contains small (10mm) aggregates of granular and coarse sand bound with mud and silt. These may represent remnants of the sediment prior to drilling.

6.37 – 6.86m Sand. Unconsolidated Coarse to granular sand with pebbly band in centre. Pebble content 1-5% at top and base, 10-20% in centre. Pebble lithologies include vein quartz, sandstones, shale and gneiss. Mud matrix is < 1%. Shell debris approx 10%, includes bivalve fragments and complete valves, coral fragments, gastropods and scaphopods. Sediment may be reworked.

6.86 – 7.37m Sand. Unconsolidated. Similar to above unit but coarsens upwards from coarse to granular sand at the base, to granular sand with pebbles at the top. Sharp contact with underlying gravel.

7.37 – 8.00m Gravel. Unconsolidated. Average clast size 10-20mm, size range up to 50mm. Maximum clast size decreases slightly upwards. Clasts angular to well rounded, majority are subangular. Lithologies include quartzite, gneiss, schist, basalt, sandstone and micaceous siltstone.

Scale 1:50



Description

12.40 – 12.50m Two large pebbles. Only recovered lithology from this depth. 70mm gneiss clast with abraded surface, 40mm amygdaloidal basalt.

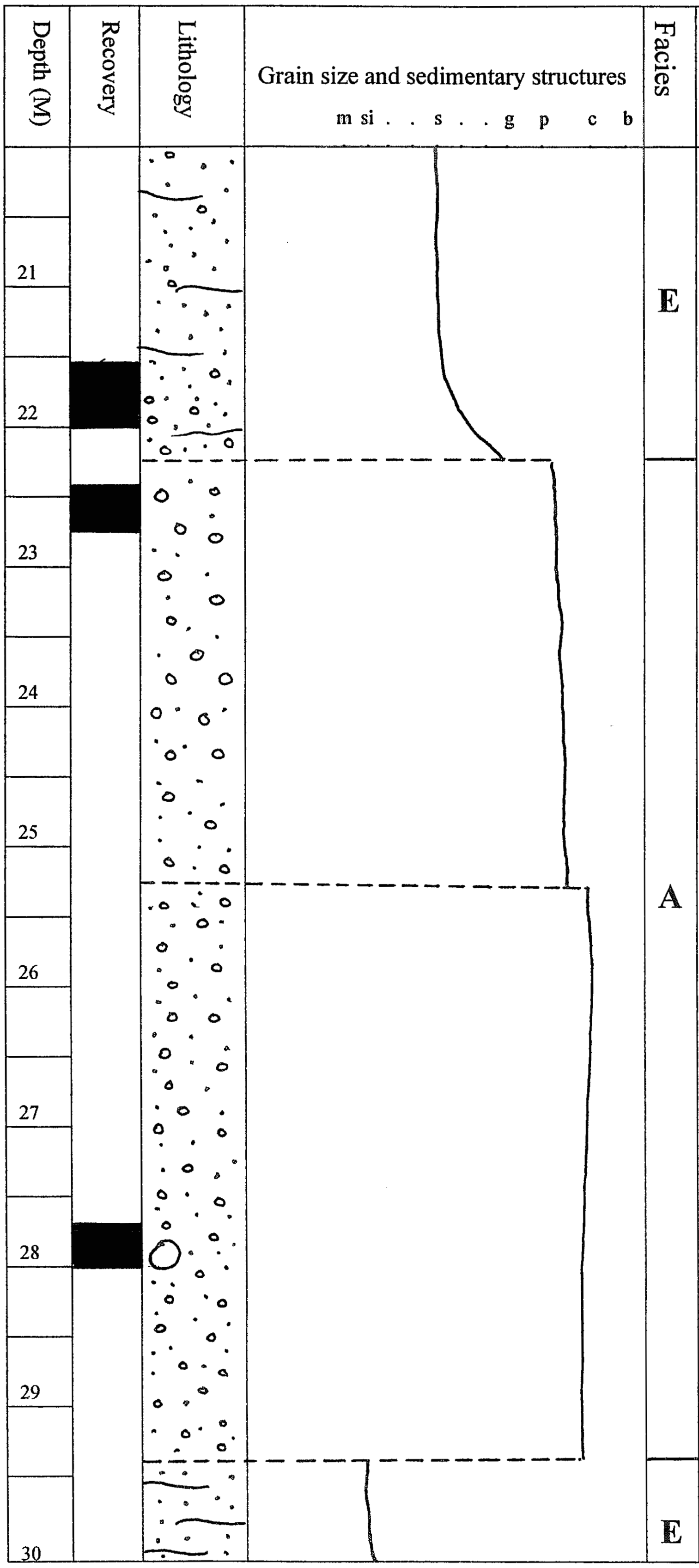
16.66 – 17.40m Muddy sand. Unconsolidated. Medium to coarse sand near base, fining upwards in to fine to medium sand. Very low mud component (< 2%). Sand approx. 85:15 quartz : lithics, 80:20 near base. quartz grains angular to subrounded. Lithics include basalts, gneiss, amphibolite, garnet, siltstone. Abundant foraminifera, bivalves, echinoid spines, brachiopod fragments, scaphopods and gastropods.

17.40 – 17.50m Cobble band. Small cobbles up to 100mm of gneiss and basalt, subangular to subrounded. No matrix recovered.

Borehole 99/5

Sheet No. 3 of 4

Scale 1:50



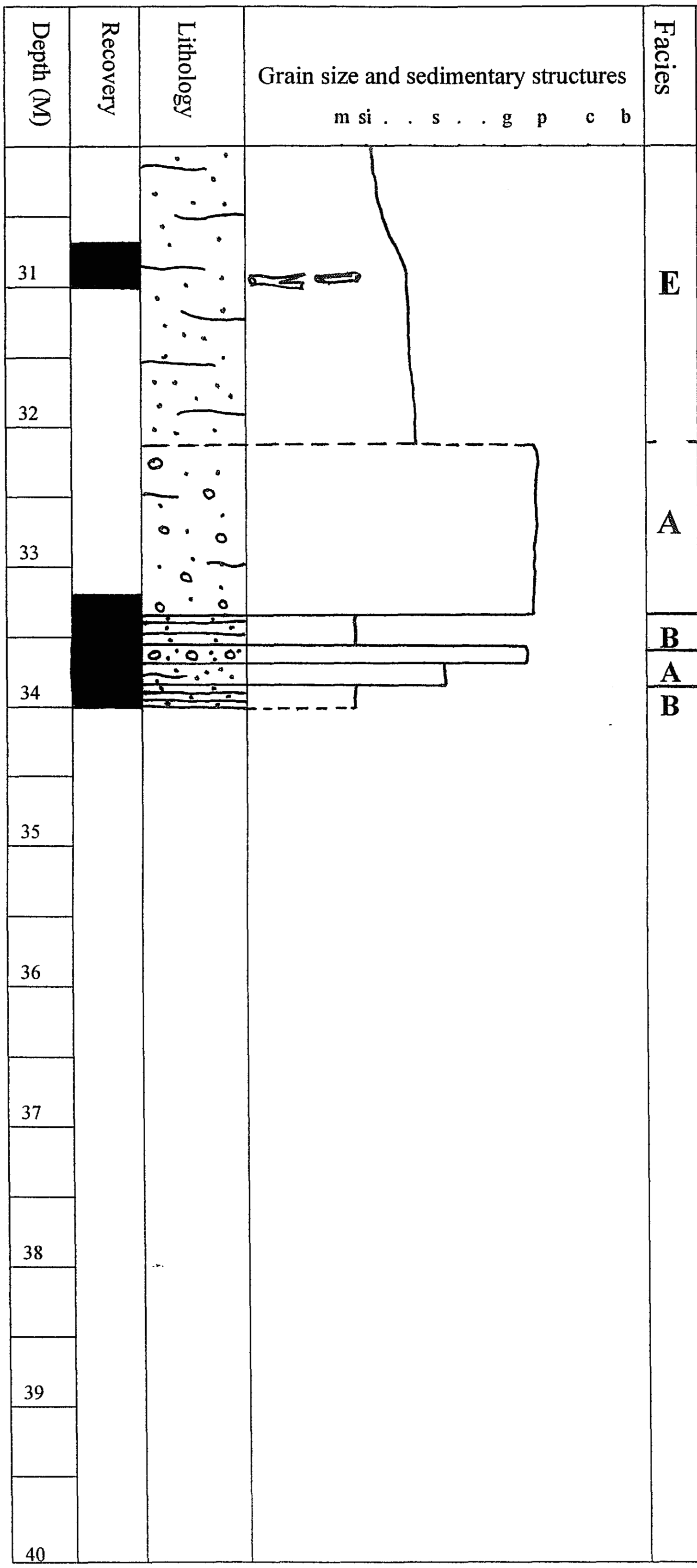
Description

21.55 – 22.00m Poor recovery. Pebbles and small cobbles. Small samples of matrix – sandy muddy silt. 30:70 mud : sand and silt. Sand fraction, fine to medium sand, quartz grains angular to subrounded, larger grains and rare granules mostly rounded to well rounded. Approx. 10% lithic grains, including gneiss, basalt, pyrite, garnet and various mafics. Pebbles and cobbles, subangular to rounded, lithologies include basalt, gneiss, sandstone.

22.44 – 22.75m Gravel. Poor recovery. Small cobbles and gravel with clasts up to 80mm, subangular to subrounded, mainly gneiss and basalt. Small samples of matrix recovered. Very fine to fine sand and silty mud. Sand fraction up to 85% quartz grains.

27.70 – 28.00m Gravel with cobbles. Sandy gravel, approx. 50% pebbles with matrix of medium to granular sand. Lithologies as above. Basalt cobble (160mm) at base .

Scale 1:50



Description

30.70 – 31.00m Muddy sand fining upwards to sandy mud. Dark green-grey (10Y3/1). Plastic sandy mud at top, approx 60:40 mud : sand and silt. Sand fraction very fine to fine, 95+% quartz grains, angular to subangular. Other grains mostly basalt and pyrite. Rare foraminifera. Possible lamination around 30.85m as sand content increases downwards. Lower part of unit 50-60% fine to very fine sand, 40-50% mud. lithic grains 10-15%, mostly mafics, mica and rare pyrite. Possible carbonaceous material. Weak reaction HCl. Possible sub-horizontal lamination or burrowing towards base.

30.83m	Shear strength	47.0 KPa
	Compressive strength	115.0 KPa
	Water content	22.60%

33.20 – 33.40m Muddy gravel. Dark green grey (10Y4/1). 60-70% granules and pebbles up to 5mm, 30-40% mud and silt, moderately well sorted Coarse fraction, angular to subrounded. Gravel clasts include basalts, gneiss, quartzite and siltstones. Small percentage of shell debris composed of mollusc fragments, corals and rare brachiopod valves.

33.40 – 33.57m Silty mud. Dark green-grey (10Y3/1) to green-black (10Y2.5/1). Plastic. Approx. 65:35 mud : very fine sand and silt. Sand fraction 90-95% quartz, some mafic grains and pyrite. Weak reaction with HCl. Too disturbed for shear/compression tests.

33.57 – 33.70m Muddy gravel. Unconsolidated. Similar to 33.20 – 33.40m. Well sorted granular sand with approx 10% small pebbles and 10% finer sand and mud.

33.70 – 33.86m Muddy sand. Dark green-grey (10Y4/1). Moderately well sorted, fine to very fine sand, 10-15% mud. Sand fraction 85-90% quartz. Lithics include micas glauconite, pyrite and rare mafics. Quartz grains angular to subangular. No reaction with HCl.
Too disturbed for geotechnical tests.

33.86 – 34.00m Silty mud. Dark green-grey (5GY3/1). Approx 95+% mud and silt, 2-5% fine to very fine sand. Very low percentage of lithic grains, mostly pyrite. Weak reaction with HCl.
Too disturbed for geotechnical tests due to cracking and drying.

4.3 Interpretation of Borehole 99/5

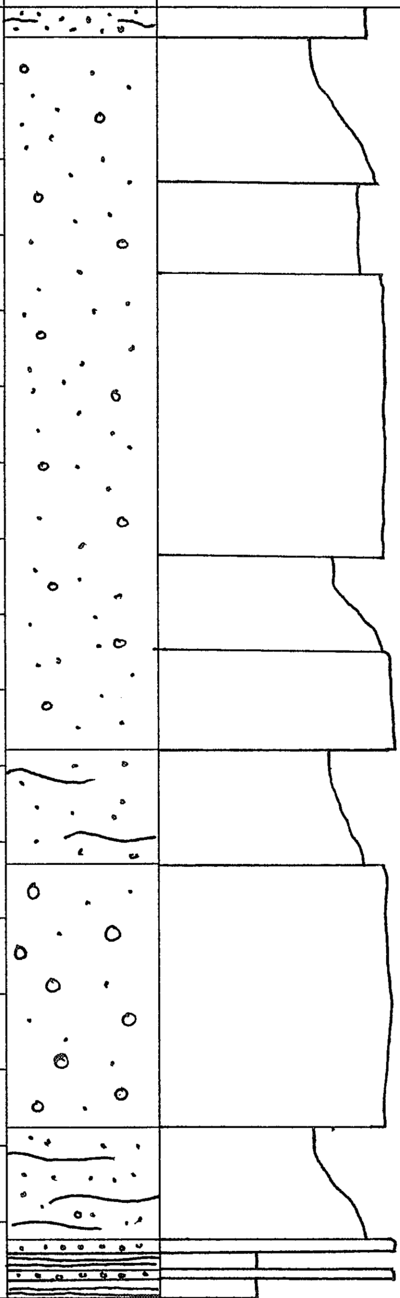
Borehole 99/5 consists of approximately 29m of sands, gravels and cobbles from facies A, overlying a 4m - 5m sequence of sands and muds of facies A, B and E. The seismic images from the borehole region are not helpful in interpreting the architecture or depositional processes of the sediments from 99/5. Applying average velocities of between 1550m/s and 1700m/s the depth to the base of the Quaternary in the core should lie between 40ms and 44ms. Unfortunately it is not possible to distinguish even this horizon from the seismic image (figure 9).

In some of the cored intervals only pebbles and cobbles were recovered, making detailed interpretation difficult. However, the majority of the sequence appears to consist of alternating facies A and facies E units, indicating repeated cycles of fining upwards sediments. This type of deposition is typical of turbidite deposits from downslope currents which, given the relatively steep slope indicated by the seismic, is a strong probability.

The facies E muddy sands at 31.0m are the only sediments observed in the entire study which show any evidence of sedimentary structures. These appear to be sub-horizontal sand-filled structures approximately 7.5mm thick which may be in-filled burrows or the remains of sandy lamination. Faunal debris is absent from this level. The remains of a calcareous fauna was present in underlying units but the broken nature of the shells, and the inclusion of coral fragments within this gravelly horizon suggests it may be transported. Within the upper sections of the core, complete valves of a thin-shelled molluscan fauna were present, suggesting at least a component of this sediment may not have been transported very far.

The pebble suite contained within sediments from both A and E facies include a variety of exotic clasts. It seems likely that these clasts are derived from glacial sediment on the shelf or from ice rafting, which may have been contemporaneous with the formation of the tubidity currents.

Summary of lithologies and depositional processes for Borehole 99/5



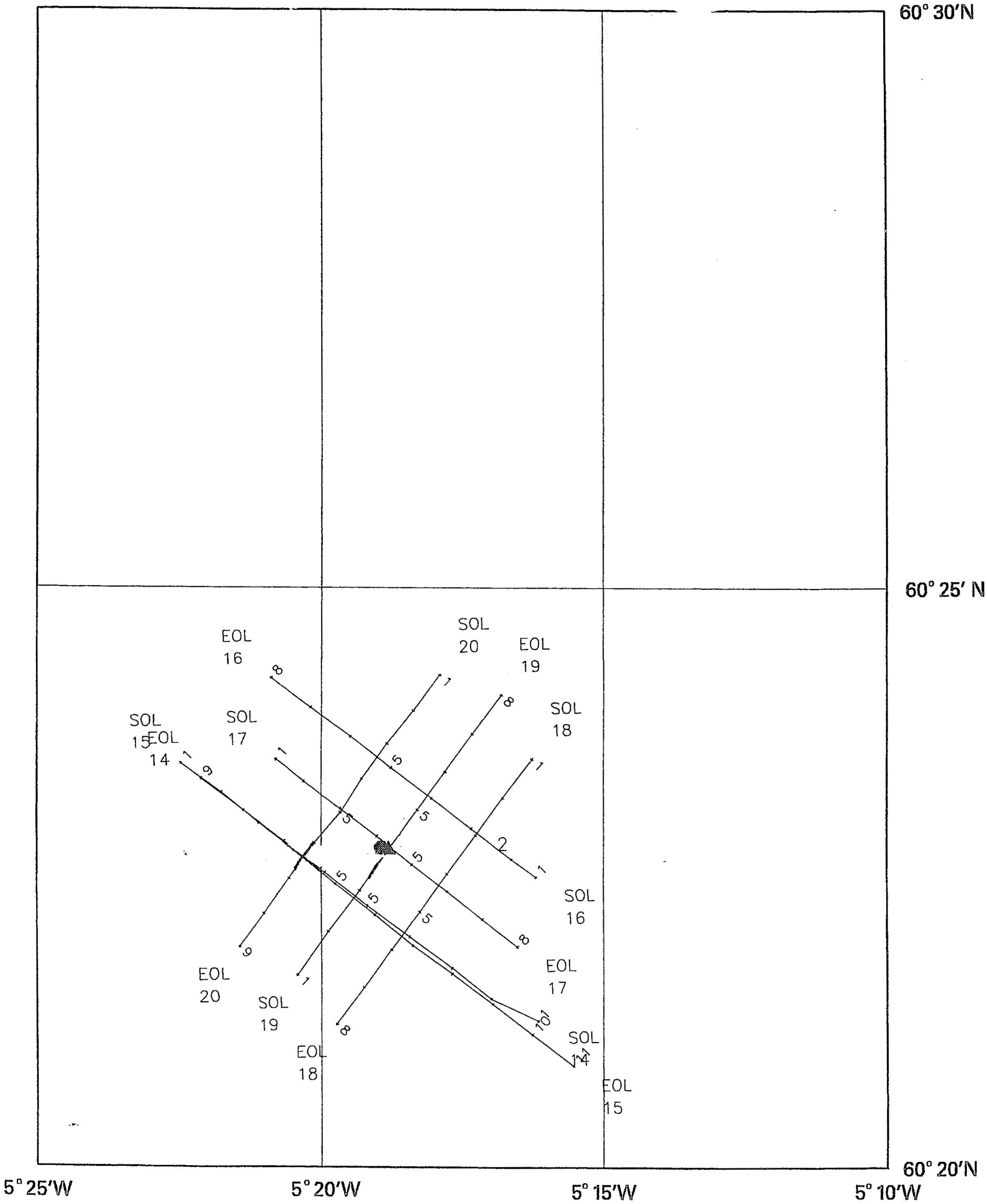
Depth	Lithology	Relative grain size	Facies	Interpretation
2, 4, 6, 8, 10, 12, 14, 16, 18, 20, 22, 24, 26, 28, 30, 32, 34, 36				
			A	0.0-0.58m A. Muddy sands and gravels. Current deposited/re-worked by contour or downslope currents.
			A	0.58 –19.50m A. Sands/muddy sands /gravels. All current deposited or re-worked. Coarseness of grains suggests downslope turbidity currents more likely as depositional process.
			E	19.50 – 22.25m E. Muddy sands/silts with pebbles. Fines upwards. Current deposited. Muddy turbidite.
			A	22.25 – 29.40m A. Poor recovery. Gravels and cobbles. Possibly a lag deposit from turbidite flow.
			E	29.40 – 32.20m E. Muddy sand – sandy mud. Fines upwards. Current deposited. Muddy turbidite.
			A/B	32.20 – 34.00m A/B. Alternating muds and sands. Suggests small scale or distal turbidites.

Borehole 99/6

Location:	Faroe-Shetland Channel, c. 85km W of Foula
Latitude:	60° 22.731' N
Longitude:	05° 18.821' W
Map Area:	Judd
Block No.	Faroes 6005/19
Date of drilling:	29th June – 1st July 1999
Water Depth:	1183m
Total depth:	36m
Depth to base of Quaternary:	c.22m

Gravity core No.	60-06/62
Latitude:	60° 22.74'N
Longitude:	05° 18.95'W
Date of sampling:	1st June 1998
Water depth:	1166m
Total depth:	2.21m

Figure 10. Location of sparker survey lines for borehole 99/6



● Location of gravity core (seabed sample)

▲ Location of borehole

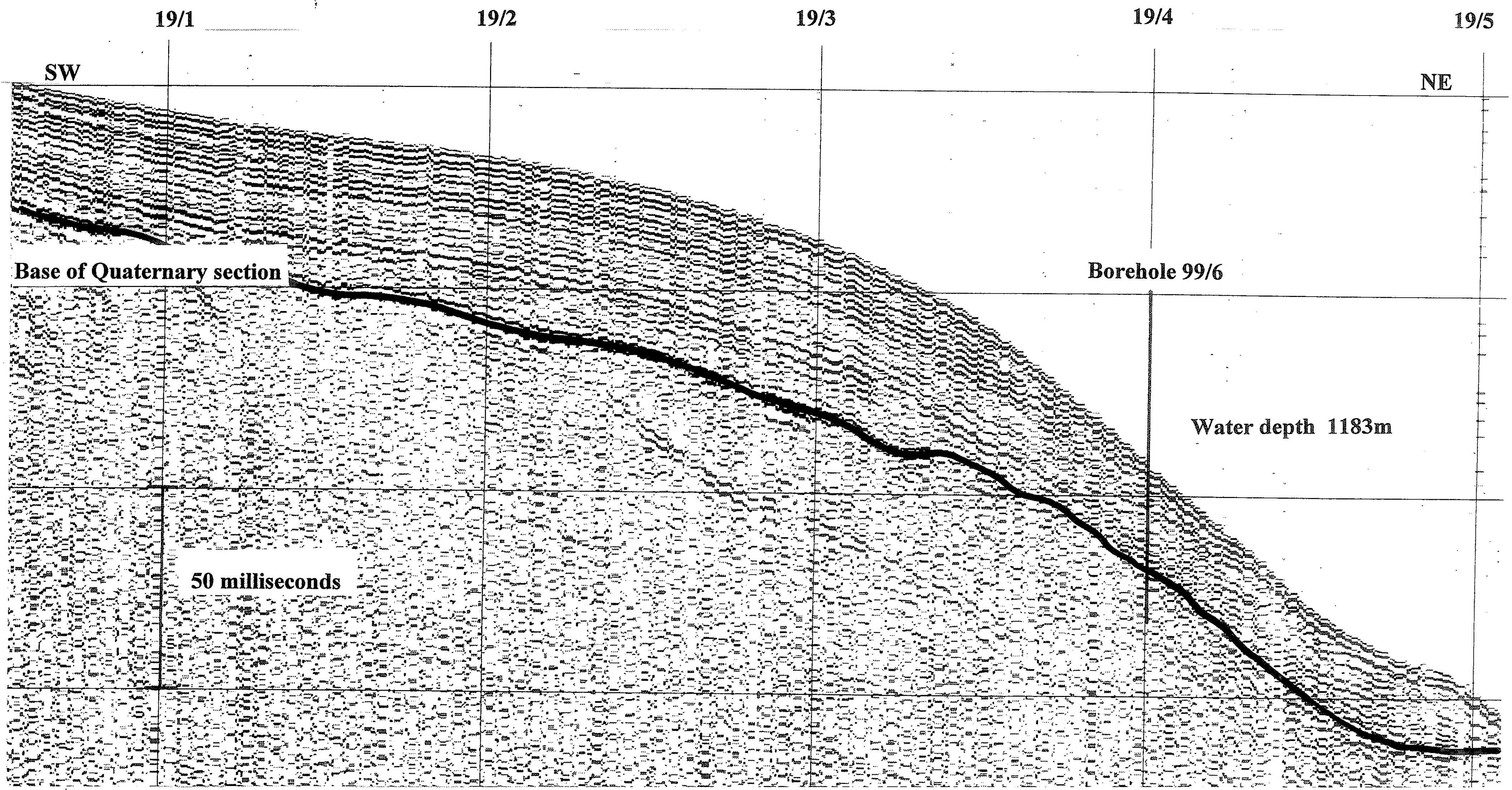
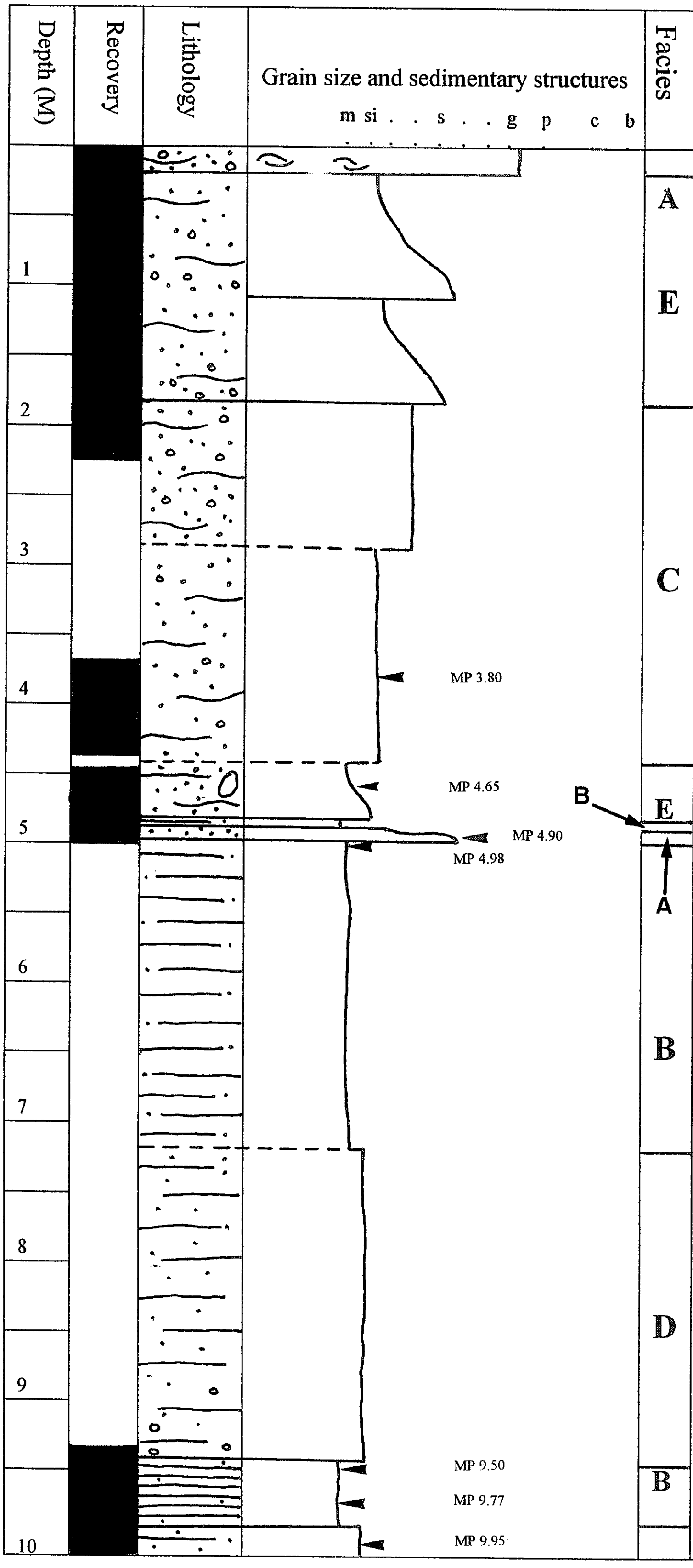


Figure 11. Seismic data from area of borehole 99/6. **Line No. 98/01-19**

Borehole 99/6

Sheet No. 1 of 2

Scale 1:50



Description

0.0 – 2.21m Data from gravity core

0.0 – 0.14m. Slightly gravelly muddy sand. Dark brown (10YR4/3), very poorly sorted, very fine to very coarse sand with subrounded gravel. Pebbles up to 10mm. Sand dominated by lithic fragments including black crystalline lithologies with angular to rounded quartz grains and 5% shell fragments dominated by foraminifera. Weak reaction with HCl. Sharp basal contact.

0.14 – 1.05m Slightly gravelly sandy mud. Dark grey (5Y4/1), very poorly sorted, fining upwards from muddy gravel to plastic mud. Very fine sand with abundant lithic grains, shell fragments and rare foraminifera. Gravel subrounded with clasts up to 50mm. Lithologies include mica schist and micaceous sandstone. No reaction with HCl. Sharp basal contact

0.6m	Shear strength	4.0 KPa
	Compressive strength	6.7KPa

1.05 – 1.78m Slightly gravelly sandy mud. Similar to above unit.

1.20m	Shear strength	6.2 KPa
	Compressive strength	7.5KPa

1.78 – 2.21m Slightly gravelly muddy sand. Olive grey (5Y4/2), very poorly sorted with lenses of poorly sorted sand. Sand grains mainly quartz, subrounded. Gravel subrounded with clasts up to 10mm. No reaction with HCl.

3.70 – 4.35m Sandy mud. Olive grey (5Y4/2). Waterlogged to liquid. Approx. 40:60 Sand : mud, sand fine to coarse, 75:25 quartz : lithic grains with lithics dominating coarser fraction. Quartz grains subangular to rounded. Lithic grains include gnt, fsp, mica, Fe stained qtz, gneiss and siltstone. Rare pebbles (< 1%) up to 40mm, subangular to subrounded. Lithologies include pale grey quartzite, gneiss and siltstones. Abundant calcareous foraminfera and rare bivalve fragments.

3.80m	Shear strength	2.0 KPa
	Compressive strength	<0.5 KPa
	Water content	36.15%

4.45 – 4.73m Sandy mud fining upwards to silty mud 80:20 mud : silt at top, 60:40 mud : sand at base. Sand fine to medium, approx 85 % quartz : 15% lithics. Quartz grains angular to subrounded Lithic grains include gnt, fsp, amph, possible glauconite. Small faceted smooth cobble at 4.57m Abundant calcareous foraminifera. Sharp basal contact.

4.65m	Shear strength	9.5 KPa
	compressive strength	18.25 KPa
	Water content	30.80%

4.73 – 4.86m Silty mud. Dark green-grey (10YG1) Approx 10% fine to medium sand. No visible foraminifera. Weak reaction with HCl

4.80m	Shear strength	14.5 KPa
	compressive strength	25.0 KPa
	Water content	25.39%

4.86 – 4.93m Muddy gravel fining upwards to sandy mud. Olive (5Y4/3) Gravel is clast supported with sandy mud matrix. clasts composed of sandy mudstone and sandstone. Matrix similar to sandy mud at top of unit. 40:60 sand : mud, very fine to medium sand with ~10% coarse sand. 75:25 quartz : lithics. Foraminifera rare at base, becoming abundant towards the top.

4.88m	shear strength	14.0 KPa
	compressive strength	10.0 KPa

4.93 – 5.00m Silty mud. Dark green-grey (10G3/1). approx. 40:60 silt : mud. Sand fraction < 5%, mostly fine sand. Rare foraminifera. Weak reaction with HCl.

4.94m	Shear strength	12.0 KPa
	Compressive strength	15.0 KPa
	Water content	28.69%

9.34 – 9.36 Silty mud. Dark green-grey (10G3/1). 40:50 silt : mud with approx 10% fine to very fine quartz-rich sand. Rare subangular pebbles up to 8mm at base. No reaction with HCl.

9.35m	Shear strength	5.0 KPa
	Compressive strength	7.5 KPa

9.36 – 9.85m Mud. Dark green-grey (5GY4/1). Plastic with up to 20% silt. Approx 5% fine sand towards base. Weak reaction with HCl at top but increases towards base. Sharp undulating basal contact. Small percentage of possible carbonaceous fragments ~ 0.2mm.

9.60m	Shear strength	12.5 KPa
	compressive strength	15.0 KPa
	Water content	31.63%

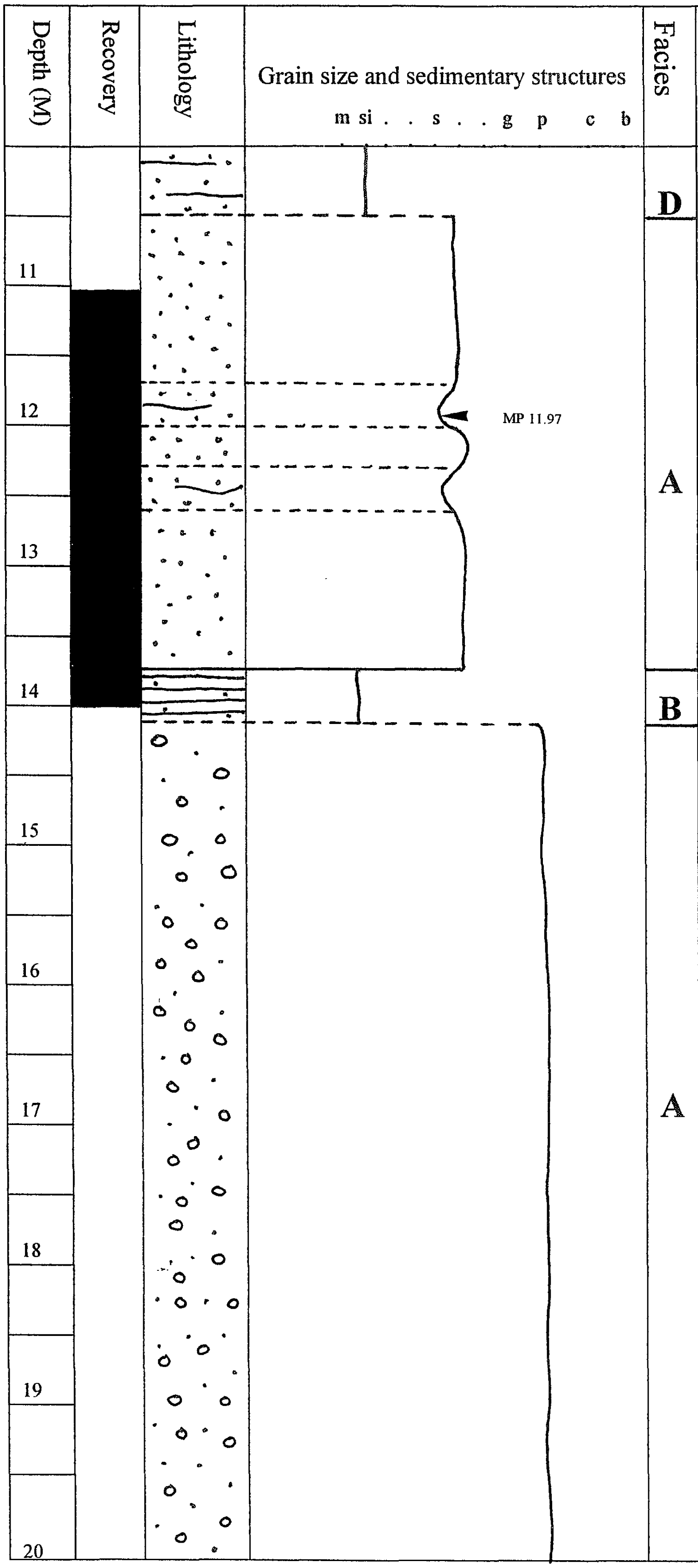
9.85 – 10.00m Silty mud. Olive grey (5Y4/2). Approx 50% mud, 30% silt and 20% fine-medium sand. Sand 50:50 quartz : lithic, quartz grains are angular to rounded. lithic grains include ~20% gnt and mafics. Sand component decreases towards base. Strong reaction with HCL. Moderate numbers of foraminifera.

9.95m	Shear strength	11.0 KPa
	compressive strength	15.7 KPa
	~~Water content~~	~~27.71%~~

Borehole 99/6

Sheet No. 2 of 2

Scale 1:50



Description

11.03 – 13.75m Coarse sand. Light yellow-brown (2.5Y6/4). Unconsolidated, structureless sand. Grain size range from medium to very coarse. well sorted very little or no matrix. 60-70 % quartz with angular to rounded grains. Approx 20% of quartz grains show Fe oxide coating. Lithic grains include high proportion of rounded mafic grains. Bands of muddy sand with ~20% mud and silt. Also contain mud balls up to 5mm. Muddy bands may represent the remains of interbedded mud units destroyed during drilling/core recovery.

11.97m	Shear strength	8.0 KPa
	compressive strength	35.0 KPa

13.50m	Shear strength	5.0 KPa
	Compressive strength	50.0 KPa
	Water content	20.21%

Engineering tests are of doubtful accuracy, unit may have been reworked during coring.

13.75 – 14.00m Mud. Dark green-grey (5G4/1). 70-80% mud, 20% silt and up to 10% fine to medium sand. Sand is 80-90% quartz. Rare foraminifera. No reaction with HCl.

13.95m	Shear strength	7.5 KPa
	compressive strength	5.0 KPa
	Water content	36.0%

No recovery between 14m and 25m. Gravel/cobbles inferred from caved fragments recovered from below 25m. Drilling difficulties encountered at approx 14m suggest the top of the gravel is at approximately 14m.

4.4 Interpretation of Borehole 99/6

Borehole 99/6 is situated on a relatively steep slope approximately 35km WSW of 99/3. The seismic data from this slope region consists of a series of thin sub-parallel reflectors which are difficult to sub-divide. In the region of the borehole the seabed appears to truncate some of the uppermost reflectors, suggesting the modern environment is erosional. The seismic image at fixed point 19/5 shows a possible small slump structure, consisting of an elipsoidal package with weak to chaotic reflectors.

The base of the Quaternary sequence lies within an interval of no recovery, but gravel and cobbles probably of facies A, were recovered as caved fragments from deeper sections and their presence is inferred from this. Below 14m drilling operations encountered problems with blocking of the bit by pebbles/cobbles (Skinner and Tulloch, 1999), suggesting the top of the facies A sands lies at approximately 14m.

Muds of facies B overlie the proposed facies A gravels. The low percentage of coarse sediment and high proportion of mud indicates there was little current activity during deposition. This unit is thought to represent background marine sedimentation combined with very distal glaciomarine deposition. The presence of arctic foraminifera in a sample from 13.91m (Hitchen, 1999) indicates that arctic conditions were probably well established at the time of deposition. The lack of coarse clastic sediment and evidence for contemporaneous current activity makes it unlikely that the fauna has been transported into the area.

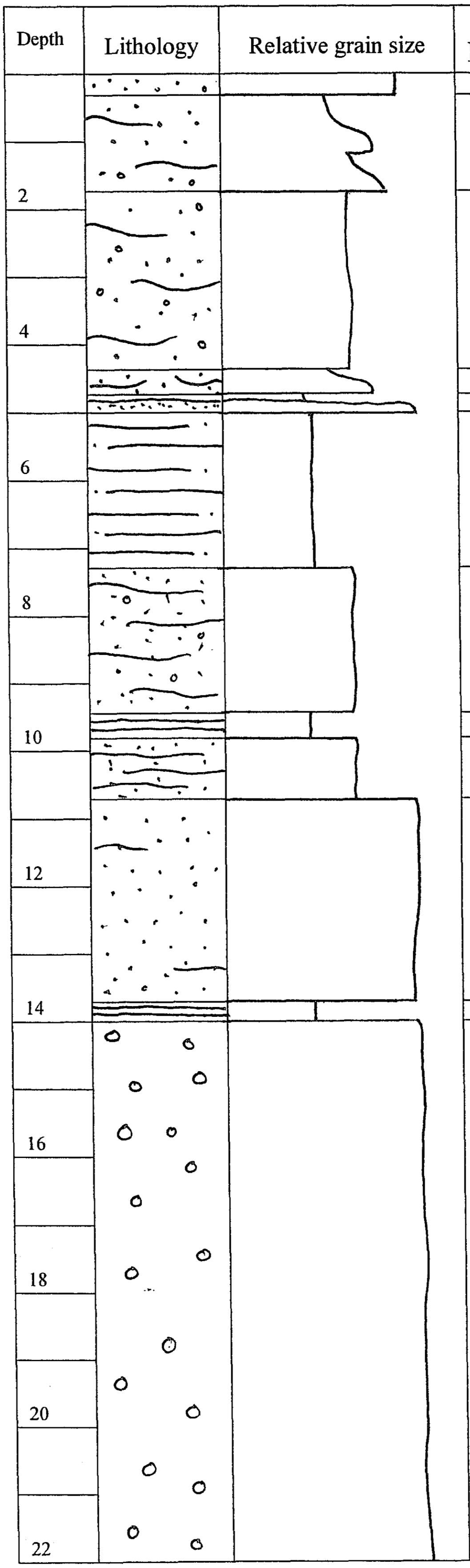
At 13.75m almost 3m of coarse, matrix poor sands of facies A overlie the facies B muds with a sharp, possibly erosional contact. These sands contain alternations of muddy sand and matrix-free sand which may be original structure or could be an artifact from drilling. The sands of facies A are interpreted as having been current deposited, which is consistent with the lack of matrix and the generally coarse to granular grain size. The most likely setting for the deposition of the sands is by downslope currents possibly within a fan-like setting similar to that seen at the base of the continental slope on the seabed image (figure 2). The lack of fan lobe structures on the seismic image does not preclude this possibility but does suggest deposition from contour currents is also a feasible origin of these sediments.

Above the coarse sand bodies, the section shows a broad and repeated fining upwards. Muddy diamictons of facies D are overlain by silty muds of facies B at 9.85m and between 5m and 9.34m. Accompanying these sediments is a cold water arctic foraminifera assemblage, indicating glacial conditions. There is also evidence of a re-worked Palaeogene fauna (see micropalaeontology section, Appendix 1). The two cycles of fining upwards sediments may reflect changes in the volume of sediment being derived from ice-rafting and glaciomarine input. Within this interval from 5m to 11.03m there is no evidence for debris or turbidity flows either from the sediments or from the seismic image. This suggests a gradual build up of the sediments rather than a rapid dumping and indicates that the ice front was probably some distance back from the shelf edge.

A change to coarser sediments occurs above 4.93m, initially with a thin sand followed by a brief return to silty muds. Above this, a series of facies E muddy sands and a facies C diamicton indicate a change in depositional conditions. The fining upwards nature of the facies E sands indicate the presence of currents. These units are interpreted as turbidites possibly derived from the more rapid build-up of glaciomarine and ice-rafted sediments. The facies C diamicton also indicates a more rapid input of coarser sediment. The absence of any debris flow packages in the seismic images suggests the diamicton may be the result of increased ice-rafting, possibly during deglaciation.

The uppermost unit of the core from 99/6 is thin facies A sand. The presence of this coarse unit at the seabed, which has a sharp basal contact, suggests that the present seabed regime is current dominated and is re-working or eroding the seabed sediments. This is supported by the high proportion of broken shell debris (approx. 5%) present in the sediment, and on a larger scale by the seismic data described above.

Summary of lithologies and depositional processes for Borehole 99/6



Facies	Interpretation
A	0.0 – 0.14m A. Muddy sand. Current deposited and/or re-worked from seafloor currents.
E	0.14 –1.78m E. Muddy sands with repeated fining upwards. Current deposited, probably from turbidity currents.
C	1.78 – 4.35m C. Muddy diamicton. Debris flow.
E	4.35 – 4.73m E. Sandy mud, fines upwards. Small turbidity flow.
A/B	4.73 – 4.93m A/B. Current re-working of muds or small sandy turbidite.
B	4.93 –7.20m B. Silty muds. Hemipelagic. Distal ice-rafting plus deposition from suspension.
D	7.20 – 9.36m D. Muddy diamicton. Debris flow from mud-rich glacigenic source.
B	9.36 – 9.85m B. silty muds. Hemipelagic. Suspended sediment with some ice-rafting.
D	9.85 – 10.50m D. Muddy diamicton. Debris flow from mud-rich glacigenic source.
A	10.50 – 13.75m A. Sands and muddy sands. Current deposited from downslope or contour currents.
B	13.75 – 14.00m B. Muds and silty muds. Hemipelagic. Suspended sediment with minor ice-rafting.
A	14.00 - ~22.00m A. Gravels and cobbles. Probably current worked lag deposit.

5.0 Conclusions

The results from the analysis of boreholes 99/3 – 99/6 and associated seismic data show a history of glacial influence extending to the base of the preserved Quaternary section. This implies that the non-glacial lower Quaternary has been removed by erosion prior to the onset of glaciation, or that it was never deposited.

Borehole 99/3 on the West Shetland Slope shows a history of repeated debris flows forming a sequence of stacked fan-shaped lobes punctuated by hemipelagic deposition. The exposure of an extensive debris flow system at the modern seabed suggests this activity continued until at least the end of glacial activity. Results from sites 99/5 and 99/6 indicate that debris flow activity was less than in 99/3. Deposition in these two areas shows evidence of turbidity currents and current re-working. It is possible that the facies D diamicton between 7m and 9.3m in 99/6 may represent a distal extension of the large debris flow seen in 99/3. The poor recovery from 99/4 makes meaningful interpretations difficult, although it would appear that current activity has been the main process responsible for deposition with little evidence for debris flows and limited ice rafting.

The clasts recovered from the various cores contain many different lithologies. However, a substantial percentage are similar to rocks seen onshore in NW Scotland. The dolomitic limestones are remarkably similar to those of the Ordovician Durness Limestone and the high percentage of red sandstones and iron oxide coated quartz grains are very likely to be of Torridonian and Devonian origin. The abundant gneiss and amphibolite clasts are almost certainly from the Lewisian basement. The origin of the Carboniferous palynomorphs recovered from 99/3 is unknown. The flora may have been derived from Carboniferous rocks which were completely removed during glaciation or have been through several cycles of deposition and erosion.

Lithologically, the boreholes show geographical change from 99/3, southwest to 99/6, 99/5 and 99/4. 99/3 is dominated by firm to soft muddy diamictons from mass flow processes and soft plastic muds. 99/6 shows a similar sequence but with a greater proportion of sandy, current deposited sediments. In boreholes 99/5 and 99/4 the diamictons and muds are almost absent, the sections being dominated by sands and muddy sands from a current-deposited origin. The presence of a coarser sandy unit at the top of all the borehole sections suggests that the present regime is one of current re-working and deposition. The re-worked nature of the sediments makes accurate dating difficult, and it is not possible to determine exactly how long these depositional conditions have been operating.

6.0 References

Boulton, G S, Peacock, J D, and Sutherland, D G. 1991. Quaternary. In Craig, G Y (Ed), Geology of Scotland (3rd edition). Geological Society of London.

Fyfe, J A and Egerton, P D. 1998. Description of cores collected in the North Atlantic, Summer 1998. BGS Technical Report WB/98/43C.

Hambrey, M J. 1994. Glacial Environments. 296 pp. UCL Press Ltd, London.

Hitchen, K. (compiler) 1999. Rockall Continental Margin Project. Shallow Borehole Drilling Programme 1999. Geological Report. BGS Technical Report WB/99/21C.

Skinner, A C and Tulloch, G J. 1999. Rockall Continental Margin Project 1999 Operations, Shallow Coring Survey. BGS Technical Report WB/99/16C.

Stoker, M S 1990. Glacially influenced sedimentation on the Hebridean slope, north-western United Kingdom continental margin. In Dowdeswell, J A and Scource, J D (Eds). Glacimarine environments: Processes and sediments. Special publication of the Geological Society of London No 53, 420 pp.

Stoker, M S, Harland, R and Graham, D K 1991. Glacially influenced basin plain sedimentation in the southern Faroe-Shetland Channel, northwest United Kingdom continental margin. Marine Geology, Vol 100, p185-199.

BRITISH GEOLOGICAL SURVEY

Natural Environment Research Council

COMMERCIAL REPORT

Report CR/00/5

Micropalaeontological Analysis of Quaternary deposits of boreholes 99/3 and 99/6

Ian P. Wilkinson (Co-ordinator), J.B. Riding, J.A. Lees Burnett & P. Bown

Geographical index
West of Shetlands and Faroes region

Subject index
Foraminifera, dinoflagellates cysts and calcareous nannofossils
Pleistocene
Biostratigraphy & Palaeoecology

British Geological Survey, Keyworth, Nottinghamshire, UK

Micropalaeontological Analysis of Quaternary deposits of boreholes 99/3 and 99/6

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1. Introduction

Two boreholes drilled during the 1999 season were sited off northern Scotland. They penetrated Pleistocene deposits before terminating in Palaeogene strata. Details are as follows:

Borehole 99/3 was situated at 60° 24.8133'N 4° 39.0639'W in the Judd mapping area (licence block 204/17). Some 52.4m of pebbly, silty and sandy muds, with subordinate sands, overlies a 3.6m thick unit of sand that passes down into gravel, which in turn rests on Tertiary strata.

Borehole 99/6 was positioned at 60° 22.7308'N 5° 18.8208'W (Faroes licence block). Approximately 11m of sandy and silty muds overlies of brown sand (about 3m thick) and a presumed conglomerate (within an interval of core loss) overlying Tertiary sediments.

Dinoflagellate cysts and foraminifera from a limited number of samples from these boreholes were recorded by, respectively, Riding *et al.* (WH99/112C; WH99/113C) and Wilkinson (WH99/144C). These data have been included herein and the conclusions expanded upon to include newly collected data. The occurrence of wood fragments, other invertebrate groups and evidence of reworked assemblages are also noted.

2. Summary

- Foraminiferal, palynological and calcareous nannofossil analyses all show that cold Arctic conditions prevailed throughout the period of deposition in both borehole 99/3 and 99/6.
- Considerable reworking can be recognised throughout the sequences, particularly at the finer grain size. Reworked palynomorphs from the Palaeozoic to Tertiary and calcareous nannofossils from the Mesozoic to Tertiary were recognised. Reworked foraminifera, the largest in dimensions of the microfossil groups, were found to be less numerous, although Cretaceous and Tertiary forms were noted.
- The age of the sequence is late Pleistocene (possibly Wolstonian or Devensian). This is consistent with foraminiferal zones N22/23 (which cannot be separated at higher latitudes) and nannofossil zones NN21/CN15.
- Horizons rich in carbonaceous material were not seen.

3. Preparation

3.1 Calcareous Microfossils

Samples examined for foraminifera were prepared using the standard techniques for non-indurated material. Samples were soaked in Teepol to aid disintegration and washed through 75micron sieves. After boiling in sodium hexametaphosphate to clean specimens further, they were allowed to dry. Picking was carried out mainly from the 125 and 250 micron size, but the coarser fraction was examined for macrofaunal remains, wood fragments and larger foraminifera and the fines were examined for smaller foraminifera.

3.2 Calcareous nannofossils

The samples comprised mainly clays and clayey sands. Preparation of the nannofossil slides was carried out as for standard suspension-smears: ~1cc of sediment was suspended in distilled water and agitated until breakdown was complete. An aliquot of the suspension was placed on a coverslip on a hotplate and allowed to dry. Two drops of distilled water were added to the coverslip and the sediment smeared using a flat-sided toothpick until a variable distribution of thicknesses of sediment were obtained. This was then dried and mounted onto a glass slide using Norland optical adhesive. Analysis was carried out at 1250x magnification on a LM with an oil-immersion objective. Two traverses of each slide were examined.

3.3 Dinoflagellate cysts and miospores

The samples were prepared using standard palynological preparatory techniques of mineral acid digestion followed by concentration of the palynomorphs. The organic residues were sieved using 10micron mesh.

4 Foraminifera

4.1 Foraminifera of Borehole 99/3

The distribution of the foraminifera recovered from 99/3 is shown in the attached text figure 1.

Four samples were taken from the sand and gravel at the base of the Quaternary sequence in borehole 99/3. The assemblages are not rich, but they are dominated by frequent to common *Cassidulina teretis*. *Cassidulina laevigata* is also well represented and although sinistrally coiled planktonic species *Neogloboquadrina pachyderma* is variably present, it is abundant at 53.55m. *Cassidulina teretis* extends throughout the Quaternary. It is found from shallow arctic, fully marine waters in high latitudes (e.g. Canada), but it has also been found on the continental slope. It prefers regions with low temperatures (of -0.5 to 0.4°C) through much of the year, but will tolerate summer waters temperatures of about 3°C. This stenohaline species favours salinities of 34-35 mille but has been recorded in waters of 32mille. *Cassidulina laevigata* often occurs in higher temperatures (up to 17°C) but this eurythermal, widespread species tolerates temperatures as low as -1°C.

Abundant sinistrally coiled *Neogloboquadrina pachyderma* and rare *Globigerina bulloides* in the sample from 53.55m also suggest Arctic conditions as the former dominates planktonic assemblages in the Arctic faunal province (where water temperatures are less than 5°C) and the latter dominates in the Subarctic province (5-10°C) (Be, 1977). In many Arctic samples, assemblage are monospecifically N. pachyderma. Coiling of N. pachyderma changes from sinistral to dextral in the Subarctic faunal province, apparently at the 7.2°C Spring surface isotherm (Ericson, 1959). In the Antarctic, this change in coiling takes place a little to the south of the "Subtropical Convergence" (Echols & Kennet, 1973). *Melonis barleeanum* (also present at 53.55m) is often found in the outer shelf and slope of Atlantic seaboard of Northwest Europe and the Norwegian-Greenland Sea. Qvale & van Weering (1985) suggested that it preferred a fine-grained substrate with a high organic carbon substrate and, if in situ, its presence in this sand and gravel is unexpected.

Near the top of the sand and gravel unit, at 52.4m, reworked foraminifera are present, apparently derived from the Eocene.

Cassidulina teretis becomes very rare or rare and patchily distributed above the sand and gravel unit, Cassidulina laevigata disappears from the record and, through to 34.22m, sinistrally coiled specimens of *N pachyderma* are frequent to abundant. The planktonic species indicate the continuation of Arctic conditions as do the benthonic species such as *Elphidium excavatum clavatum*, *Cassidulina reniforme* and *Haynesina orbiculare* in the 47.04-50.87m interval. *Bulimina marginata* also occurs here and is usually considered to be a boreal to temperate species in its present day distribution (but its most northern occurrence is in Spitsberg where the effect of the North Atlantic Drift has taken it to higher latitudes) These benthonic taxa are all shallow water species (generally inner shelf) and their very rare occurrence suggests that they have been washed into the area from elsewhere. A similar fauna was found at 34.7m. although it was at this horizon that the only specimen of dextrally coiled *N pachyderma* was found. Very rare, small chips of black woody material was seen at 37.78m.

A barren interval occurs between the samples at 41.27 and 44.60m depth. The reason for this is unclear, but this interval straddles the thin medium to coarse grained sand and the pebbly mudstones (diamict) shown on the borehole log.

At 34.22m several species appear for the first time in the borehole, although all species are very rare. Although outer shelf to slope species have already been mentioned, it is this sample that very deep water species occur for the first time. *Paromalina crassa* is essentially an upper bathyal species but is also found on the slope. In the Porcupine Seabight and South western Approaches, for example, it is found living in water depths of between 700 and 1400m (Weston, 1985), 1134m off the Canary Islands (Brady, 1884) and off the eastern Seaboard of the USA, where it occurs as shallow as 258m of water (Cushman, 1931). However it is found as a single specimen in the present borehole, accompanied by shallow water taxa such as *Bulimina gibba* and *Elphidium asklundi.*

All samples through to the top of the borehole contained consistent but rare sinistral N. pachyderma and very rare to rare *Cibicides lobatulus*. Of the benthonic taxa, shallow water Boreo-arctic species such as *Elphidium excavatum clavatum, Elphidium groenlandicum* and *Virgulina loeblichi* occur together with sub-boreal to temperate *Ammonia batavus* and temperate *Spiroplectammina wrighti*. There appears to be a mixing at this horizon.

At 12.9m rare *Planulina ariminensis* appears. This species occurs on the outer shelf to about 1000m with maximum appearances in water depths of between 300 and 500m, but it has an upper depth limit of 60m in the Gulf of Mexico (Morkhoven et al., 1986). It is widely distributed in the northern Atlantic, Gulf of Mexico, South Atlantic and Mediterranean. In the Western Approaches and Porcupine Seabight the species has been found living between 442 and1002m. This is a further deeper water species. Reworking is indicated by the presence of a specimen of ?*Globigerinelloides* from the Cretaceous and Cibicidoides sp from the Tertiary.

4.2 Foraminifera of Borehole 99/6

The assemblages in borehole 99/6 are much less diverse than borehole 99/3. Their distribution is shown in the attached text figure 2.

The lowest sample examined, at 13.91m contained only rare sinistral *Neogloboquadrina pachyderma* and the sample from 11.97m was found to be barren. The former sample was of a silty clay that rested on the presumed conglomerate and Arctic conditions can be tentatively suggested on the basis of the coiling direction of the planktonic foraminifera. The latter sample was from a medium to coarse sand and the absence of foraminifera probably reflects facies.

At 9.77 and 9.95m, the rare sinistral *N. pachyderma* are accompanied by common to abundant *Cassidulina teretis*, although preservation is not good. Reworking of apparently Palaeogene foraminifera can be recognised at a depth of 9.77m and only reworked material was found at 9.55m. Very rare wood chips were noted at 9.77m. *Cassidulina teretis* extends throughout the Quaternary, and is found living on the continental shelf and slope in high latitudes where low temperatures (of -0.5 to 0.4°C) are present throughout much of the year, although it will tolerate summer waters temperatures of about 3°C. This species, together with sinistral *Neogloboquadrina pachyderma* confirms that arctic conditions prevailed.

At and above 4.98m there is an abrupt increase in the richness of the fauna, although this is predominantly the result of an increase in the proportion of planktonic *N pachyderma*, which dominates faunas. *Cassidulina teretis* become rare above this horizon and the arctic shelf species *Elphidium excavatum clavatum* appears in small numbers.

Another horizon of reworked foraminifera was identified at a depth of 4.9m where late Cretaceous *Gavelinella thalmanni* and *Globorotalites michelinianus* were found. They occur with very rare dextral *N. pachyderma* and *Bulimina marginata*, both of which are associated with temperate to boreal conditions rather than the Arctic.

The occurrence of *Pullenia bulloides* at a depth of 4.65m is worthy of note as it is the only evidence of deeper waters in the borehole. This cold water outer shelf to bathyal infaunal detrivore shows a preference for muddy substrates. It has been recorded living in fully marine salinities of the North and South Atlantic as well as the Pacific and abundantly between 1000 and 1400m off Norway (Mackensen et al., 1985). It appears to show a preference for temperatures up to about 4°C.

The highest sample examined from borehole 99/6 was taken at a depth of 3.80m. Although very rare, species indicative of shallow warmer waters occur. *Ammonia batavus* is a shallow euryhaline species with a widespread distribution throughout the temperate and boreal, inner shelf areas of the North Atlantic. *Bulimina gibba* occurs in inner and middle shelf waters in temperate to boreal parts of the North Atlantic. Very rare wood chips were found in the sample from 3.80m.

5. Palynology and palynofacies

5.1 The palynology of the Quaternary of borehole 99/3

BGS borehole 99/3 was drilled during June 1999 and proved 54m of Pleistocene diamicts and mud-rich suspension deposits which are underlain by 3m of sands and cobbles. Below the sand/cobble horizon, Palaeogene strata were cored to TD at 166.5m.

Twelve samples were taken from this borehole, all from the Quaternary succession. The samples yielded variably abundant kerogen and palynomorph associations. Both indigenous and allochthonous palynomorphs are present. The distribution of kerogen types and palynomorphs of different ages are illustrated in Figures 3 and 4 respectively. Generally the samples proved abundant and well-preserved palynofloras. Unequivocally Quaternary dinoflagellate cysts and pollen are sporadically present. However, reworked miospores and marine microplankton of Carboniferous to Palaeogene age were consistently observed.

The kerogen assemblages are dominated by wood and other plant tissue including palynomorphs. Amorphous organic material varied from rare (depths 53.55 and 44.26m) to relatively common (depths 53.75, 53.10-44.60, 31.85). It is clear, however, that a major oil source rock has not been extensively incorporated into this Quaternary succession due to the lack of abundant levels of amorphogen. The kerogen suites observed are largely gas-prone on the basis of the dominance of woody tissue. Most levels examined should be suitable for carbon dating. However the large levels of allochthonous palynomorphs observed (see below) means that much of the woody/carbonaceous material may have been similarly stratigraphically recycled. This would mean that any data from carbon dating may be spurious. Consideration should be given to AMS dating of known indigenous shelly faunas/microfaunas. Abundant resistant mineral grains were noted in samples at 41.27m and 37.78m (Figure 3).

All the twelve samples yielded relatively abundant palynomorph floras. These suites are a mixture of indigenous and recycled forms. Carboniferous, Permo-Triassic, Jurassic, Cretaceous and Palaeogene palynomorphs were noted. This spectrum is typical of Quaternary successions which yield allochthonous palynofloras (Riding *et al.*, 1997; 2000). These reworked floras indicate that the ice traversed Carboniferous, Jurassic, Cretaceous and Palaeogene strata in the case of diamictites. In water-lain sediments it means that the material was introduced by fluvial processes. Carboniferous spores were encountered consistently. Only a single Permo-Triassic specimen was observed. Jurassic reworking is absent or questionable at 53.75-53.10m. Palynomorphs from the Cretaceous are sparse to absent in samples 44.26-12.35m. Palaeogene dinoflagellate cysts are highly sporadic, unequivocally present only at 47.04, 44.60, 37.78, 34.22 and 12.65m (Figure 4).

Quaternary dinoflagellate cysts are relatively rare in samples at 53.75-37.78m inclusive. These floras are low in diversity and generally include *Achomosphaera andalousiensis, Bitectatodinium tepikiense, Brigantedinium cariacoense, Brigantedinium simplex, Brigantedinium* spp., *Impagidinium aculeatum*, *Lingulodinium machaerophorum, Operculodinium centrocarpum* and *Spiniferites* spp. Sample 4, however, yielded abundant 'round-brown' protoperidiniacean forms referable to *Brigantedinium* spp. The majority of these are *Brigantedinium simplex.* This association is indicative of cold, arctic, glacial conditions with seasonal or permanent sea-ice (Harland, 1992). Samples at 31.85 and 12.90m also yielded *Brigantedinium* but in significantly lower proportions than sample 34.22m. The sample at 12.65m produced an abundant indigenous dinoflagellate cyst flora which is dominated by *Bitectatodinium tepikiense*. This species in large numbers and in low diversity associations is indicative of cold, glacial climates (Harland, 1992). Its association with *Brigantedinium cariacoense* means therefore that the sample at 12.65m is either of Wolstonian or Devensian age (see below).

The consistent presence of *Spiniferites* suggests a shelf setting. This would be expected of a succession dominated by diamictites. *Brigantedinium cariacoense* is indicative of the Late Pleistocene (Harland, 1992). Typically Quaternary pollen is generally rare and includes *Alnipollenites, Caryapollenites, Inaperturopollenites hiatus* and *Tilia*. These forms are also present in the Palaeogene so could be reworked.

Palaeogene reworking was noted in samples at 47.04, 44.60, 37.78, 34.22 and 12.65m (Figure 4) and largely comprises typically Eocene dinoflagellate cysts. Species recognised include *Apectodinium* sp., *Charlesdownia tenuivirgula, Cordosphaeridium gracile, Deflandrea* spp., *Dracodinium* sp., *Hystrichokolpoma* sp., *Samlandia chlamydophora, Wetzeliella articulata* and *Wetzeliella* spp. This assemblage is characteristic of the Eocene to early Oligocene (Powell, 1992). This means that the majority of the Palaeogene reworking is probably derived from the Stornsay Group.

Cretaceous palynomorphs were observed in samples at 53.75-44.60, 37.78 and 34.22m in significant numbers (Figure 4). The long-ranging dinoflagellate cyst *Odontochitina operculata* is consistently present. The typically Lower Cretaceous schizalean spore genus *Cicatricosisporites* is also present. Lower Cretaceous dinoflagellate cysts are also present sporadically. These include *?Batioladinium jaegeri, Bourkodinium* sp., *Cribroperidinium edwardsii, Cribroperidinium* spp., *Epelidosphaeridia spinosa, Muderongia* spp., *Ophiobolus* sp., *Palaeoperidinium cretaceum* and *Pseudoceratium pelliferum*. Most of these forms are probably derived from the Valhall Formation; the occurrence of *Epelidosphaeridia spinosa* at 53.55m is indicative of the late Albian to mid Cenomanian (Costa and Davey, 1992).

Jurassic palynomorphs are present in most of the samples studied. Miospores are present, including *Callialasporites* spp., *Cerebropollenites macroverrucosus, Classopollis classoides, Ischysporites vaerigatus* and *Perinopollenites elatoides*. These are long ranging within the Jurassic and Lower Cretaceous. However, some age-diagnostic dinoflagellate cysts were observed. These are *Nannoceratopsis gracilis* (at 47.04m; Toarcian-Bajocian), *Gonyaulacysta jurassica* subsp. *adecta* (at 37.78m; Bathonian-Callovian), and *Glossodinium dimorphum* (at

41.27m; mid Oxfordian-Portlandian). This indicates the multiphase reworking of Toarcian-Bajocian, probable Callovian and Oxfordian-Portlandian sediments (Riding and Thomas, 1992). A tetrad of the spore *Kraeuselisporites reissingeri* was encountered in the sample at a depth of 37.78m. This species is restricted to the Rhaetian (Upper Triassic) to the Sinemurian.

A specimen of taeniate pollen was recorded in at 53.55m, indicating the input of Permian-Triassic strata.

Carboniferous spores are present in all the horizons examined and are especially common in samples at 44.60m and 41.27m (Figure 4). The majority are relatively long ranging genera such as *Circulizonates, Densosporites* and *Lycospora*, however Westphalian markers such as *Endosporites* are occasionally present (e.g. at a depth of 53.55m). Other Carboniferous genera observed include *Cirratritadites*, *Cristatisporites* and *Tripartites*.

5.2 The palynology of the Quaternary of borehole 99/6

BGS borehole 99/6 is located in the Faroe-Shetland Basin and was drilled to prove the succession above and below an intra-early Eocene unconformity. The borehole proved c.22m of heterolithic Quaternary sediments which are underlain by early Eocene green-grey mudstones to 39m.

The eight samples studied yielded variably abundant kerogen and palynomorph associations. Both indigenous and allochthonous palynomorphs are present. The distribution of kerogen types and palynomorphs of different ages are illustrated in Figures 5 and 6 respectively. Generally the samples proved abundant and well-preserved palynofloras. Unequivocally Quaternary dinoflagellate cysts and pollen are sporadically present. However, reworked miospores and marine microplankton of Carboniferous, Jurassic, Cretaceous and Palaeogene age were consistently observed.

The kerogen associations are dominated by wood and plant tissues of various types (including palynomorphs). Amorphous organic material varied from entirely absent to present in relatively low proportions. It is clear that a major oil source rock has not been extensively incorporated into this Quaternary succession due to the relative paucity of amorphogen. The kerogen suites observed are largely gas-prone on the basis of the dominance of woody tissue. Most of the samples examined should be suitable for carbon dating. However the large levels of allochthonous palynomorphs observed (see below) means that much of the woody/carbonaceous material may have been reworked. This would mean that any data from carbon dating may be inaccurate. Consideration should be given to AMS dating of known indigenous shelly faunas/microfaunas. Resistant mineral grains were noted sporadically (Figure 5).

All samples yielded relatively abundant palynomorph floras. These suites are a mixture of indigenous and recycled forms. Carboniferous, Jurassic, Cretaceous and Palaeogene marker species were noted. This spectrum is typical of Neogene and Quaternary strata which yield allochthonous palynofloras (Riding *et al.*, 1997; 2000). These reworked floras indicate that, in the case of the diamictites, the ice traversed Carboniferous, Jurassic, Cretaceous and Palaeogene strata.

Quaternary dinoflagellate cysts are rare and low in diversity in samples at depths of 4.65-9.77m inclusive and 11.97m. These floras generally include *Spiniferites* spp. and occasionally *Achomosphaera andalousiensis, Brigantedinium simplex* and *Operculodinium centrocarpum.* Samples at depths of 3.80m and 9.95m, however, yielded abundant 'round-brown' protoperidiniacean forms, dominantly *Brigantedinium simplex.* These assemblages, if representing *in situ* occurrences, are indicative of cold, arctic, glacial conditions with seasonal or permanent sea-ice (Harland, 1992). The presence of *Spiniferites* suggests a shelf setting. This would be expected of a succession dominated by diamictites. *Brigantedinium simplex* is indicative of the Mid to Late Pleistocene (Harland, 1992). Typically Quaternary pollen is extremely rare and comprises *Alnipollenites, Caryapollenites* and *Tilia.* These forms are also present in the Palaeogene so could be reworked.

The Palaeogene reworking is largely dinoflagellate cysts from the Eocene. Species recognised include *Apectodinium augustum, Cordosphaeridium gracile, Deflandrea* spp., *Diphyes ficusoides, Eatonicysta ursulae, Homotryblium* spp., *Thalassiphora pelagica, Wetzeliella articulata* and *Wetzeliella* spp. Of these species, *Eatonicysta ursulae* (at 3.80m) and *Diphyes ficusoides* (at 11.97m) are confined to the Eocene (Powell, 1992). This means that the majority of the Palaeogene reworking is interpreted as being from the Stornsay Group.

Cretaceous dinoflagellate cysts and spores were observed throughout in significant numbers (Figure 5). The long-ranging dinoflagellate cyst *Odontochitina operculata* is consistently present. The majority of the Cretaceous palynomorphs are Lower Cretaceous dinoflagellate cysts. However, schizalean spores such as *Appendicisporites* and *Cicatricosisporites* are also present. Several forms within the Ryazanian to Albian interval are not age diagnostic (e.g. *Cribroperidinium edwardsii, Endoscrinium campanula* and *Palaeoperidinium cretaceum*). In the sample at 4.90m, the occurrences of *Endoceratium turneri, Epelidosphaeridia spinosa, Oligosphaeridium 'quadrum'* and *Pseudoceratium 'eopelliferum'* is indicative of the incorporation of Ryazanian to early Hauterivian and late Aptian to Albian strata (Costa and Davey, 1992). This multiphase reworking is a common phenomenon. Further reworked Lower Cretaceous dinoflagellate cysts include *Batioladinium jaegeri* (at 9.77m), *Kleithriasphaeridium corrugatum* (at 9.77m), *Muderongia staurota* (at 9.77, 9.95, 11.97m), *Protoellipsoidinium spinosum* (at 9.50 and 9.77m) and *Pseudoceratium pelliferum* (at 4.98m). *Muderongia staurota* ranges from the late Hauterivian to Barremian (Costa and Davey, 1992). The majority of these forms are most probably derived from the Valhall Formation.

Jurassic palynomorphs are not as common as those from the Cretaceous or Palaeogene. Several miospores are present but are long ranging within the Jurassic and Lower Cretaceous. These include *Callialasporites* spp. and *Cerebropollenites macroverrucosus*. However some age-diagnostic dinoflagellate cysts were observed. These are *Nannoceratopsis deflandrei* (samples at 4.90 and 9.77m; late Pliensbachian-Bajocian), *Scriniodinium crystallinum* (late Callovian-earliest Kimmeridgian; sample at 9.50m) and *Wanaea acollaris* (at 4.90m; late Bajocian-Callovian). This indicates a multiphase reworking of late Pliensbachian-Bajocian and probable Callovian sediments (Riding and Thomas, 1992).

Carboniferous spores are present in all the horizons examined except the sample at a depth of 11.97m (Figure 5). The majority are relatively long ranging genera such as *Circulizonates, Densosporites* and *Lycospora*, however Westphalian markers such as *Endosporites* are present. Other Carboniferous forms include *Cirratritadites* spp. and *Cristatisporites* spp.

6 Calcareous nannofossils

6.1 Calcareous nannofossils of Borehole 99/3

Twelve sample between 12.35m and 53.75m were examined. All of the samples were productive (Text Figure 7a). The assemblages were dominated by reworked Mesozoic taxa, with Tertiary taxa forming only a small component of the reworked assemblages, whilst the Quaternary taxa formed a significant component in only three samples (12.65m, 31.85m, 34.22m). Preservation was very poor-moderate throughout, whilst abundances varied from very-low to low-moderate.

Emiliania huxleyi was present throughout the sequence, indicating Nannofossil Zone NN21 of Martini (1971) (equivalent to CN15 of Okada & Bukry, 1980), *i.e.* latest Pleistocene to Early Holocene.

6.2 Calcareous nannofossils of Borehole 99/6

Out of eight samples examined (Text Figure 7b), between 3.80m and 11.97m, two were completely barren of nannofossils (4.90m, 11.97m), one was barren of Quaternary nannofossils (4.98m), and a further two contained only very rare occurrences of Quaternary nannofossils: 9.50m contained single specimens of *Coccolithus pelagicus* and *Emiliania huxleyi*, whilst 9.77m contained a single specimen of *C. pelagicus* and two specimens of *Gephyrocapsa ericsonii*.

Reworked Mesozoic nannofossils were abundant to common throughout the sequence (except in the barren intervals), with lesser amounts of Tertiary taxa being present. Preservation varied from very poor-poor to poor-moderate, whilst abundance was mainly very low but with low-moderate and moderate intervals.

E. huxleyi was present throughout the sequence, indicating Nannofossil Zone NN21 of Martini (1971) (equivalent to CN15 of Okada & Bukry, 1980), *i.e.* latest Pleistocene to Early Holocene.

7. Conclusions

7.1 Foraminifera

In conclusion, Arctic conditions are indicated throughout the sequence in borehole 99/3, although there is some rather weak evidence for phases of warming at 34.7 and 28.81m. The faunas recovered from borehole 99/3 indicate that reworking has occurred. Not only is there evidence of cold and warm or shallow and deep water Quaternary taxa being brought together, but at 53.55, 52.40, 12.90m and 12.65m Palaeogene and questionably Cretaceous taxa are reworked.

In terms of the age of the assemblages in borehole 99/3, the planktonic foraminiferal zone NSP16b of King (1989) for the North Sea, defined by the occurrence of abundant sinistral *N. pachyderma*, can be recognised. King also recognised benthonic foraminiferal zone NSB16x based on the occurrence of *Nonion labradoricum*. This species is confined to the Pleistocene to Recent, but in the present borehole was recovered only from depths 28.81 and 34.70m. In terms of the 'international zonal scheme' of planktonic foraminiferal zones, which was defined essentially on lower latitude taxa and distributions, the whole sequence is regarded as falling within zones N22/23, although the zonal indices were not present. The assemblages are Pleistocene in age.

Arctic conditions are indicated throughout borehole 99/6, although there is weak evidence for ameliorated conditions at 4.9 and 3.8m. Benthonic taxa are predominantly shelf forms, but at 4.65m an outer shelf to bathyal species was found. Periods of more active reworking occur at 9.50-9.77 and 4.9m where, respectively, Palaeogene and late Cretaceous species were found.

The age of the all the assemblages in borehole 99/6 is Pleistocene. Planktonic foraminiferal zone NSP16b of King1989 for the North Sea, defined by the occurrence of abundant sinistral *N. pachyderma*, can be recognised. The whole sequence is regarded as falling within the 'international planktonic foraminiferal zones' N22/23, although the zonal indices were not present.

7.2 Palynology

The samples studied from boreholes 99/3 and 99/6 yield similar associations of kerogen macerals and palynomorphs. The kerogen is largely of woody type, with amorphogen being generally relatively rare. The indigenous palynomorphs are dominated by dinoflagellate cysts. These floras are normally indicative of cold, glacial conditions and are of Mid-Late or Late Pleistocene age. The residues also include significant levels of allochthonous (reworked) palynomorphs. These are of Carboniferous, Permo-Triassic, Jurassic, Cretaceous and Palaeogene age. These type of recycled floras are also typical of the Pliocene and Pleistocene of the southern North Sea Basin and can provide data on the provenance of the sediment. If the allochthonous palynomorphs are from diamictites, their source has to be from a general northerly direction; by contrast, fluvial input may be from any direction. If ice-derived, the glaciers must have traversed a wide variety of bedrock types as the possibility of multiple reworking is extremely unlikely (Riding *et al.*, 1997). This phenomenon is whereby, for example, Carboniferous spores are reworked into Mesozoic strata and have been incorporated into the Quaternary sediments via Mesozoic clasts.

7.3 Calcareous Nannofossils

Both boreholes can be dated as Late Pleistocene-Holocene (NN21/CN15), based on the presence throughout of *Emiliania huxleyi* (the first occurrence of which marks the base of these zones).

Intervals which were barren of Quaternary nannofossils can be tentatively interpreted as representing ice-rafted detritus deposited during advances of the polar front (Hine & Weaver, 1998).

Hine & Weaver (1998) described a number of acme intervals which can be used to subdivide the Quaternary, with NN21 being divisible by a switch from large *Gephyrocapsa* species to *E. huxleyi* dominance (which continues into the present day). The *Gephyrocapsa*s in the boreholes studied here are small (except for a single occurrence of *Gephyrocapsa oceanica* in Borehole 99/3, 53,25m), but *E. huxleyi* does appear to increase in relative abundance at and above 34.22m. This may or may not be significant, since earlier Quaternary reworking has possibly affected these assemblages. In addition, Hine & Weaver (1998) reported an increase in abundance (to >60%: Gard, 1989; Baumann & Matthiessen, 1992) of *Coccolithus pelagicus* in Early Holocene high-latitude assemblages. Such abundances were not identified in this study, and this may indicate that the BGS material can be restricted to a Late Pleistocene age.

8. References

Baumann, K.-H. & Matthiessen, J. 1992. Variations in surface water mass conditions in the Norwegian Sea: Evidence from Holocene coccolith and dinoflagellate cyst assemblages. *Marine Micropaleontology*, **20**: 129-146.

Be, A.W.H. 1977. An ecological, zoogeographic and taxonomic review of Recent planktonic foraminifera. In: Ramsey, A.T.S. (ed) *Oceanic Micropalaeontology*, 1-100. [Academic Press, London].

Brady, H.B. 1884. Report on the foraminifera dredged by HMS Challenger during the years 1873-1876. *Reports of the Scientific Results of the Voyage of HMS Challenger*, Vol. IX (Zoology), 814pp.

Costa, L. I. and Davey, R. J. 1992. Dinoflagellate cysts of the Cretaceous System. *In:* Powell, A. J. (ed.). *A stratigraphic index of dinoflagellate cysts.* British Micropalaeontological Society Publications Series. Chapman and Hall, London, 99-153.

Cushman, J.A. 1931. The foraminifera of the Atlantic Ocean; part 8- Rotaliidae, Amphisteginidae, Calcarinidae, Cymbaloporettidae, Globorotaliidae, Anomalinidae, Planorbulinidae, Rupertiidae and Homotremidae. *Bulletin of the United States National Museu*m, **104**, 1-179.

Echols, R.J. & Kennet, J.P. 1973. Distribution of foraminifera in the surface sediments. In: Bushnell, V. (ed.) Marine sediments of southern oceans. *American Geographical Society, Antarctic Map Folio series* **17**, *13-17.*

Ericson, D.B. 1959. Coiling direction of Globigerina pachyderma as a climatic index. *Science*, **130**, 219-220.

Gard, G. 1989. Variations in coccolith assemblages during the Last Glacial Cycle in the High and Mid-Latitude Atlantic and Indian Oceans. *In*: J.A. Crux & S.E van Heck (Eds). *Nannofossils and their applications*. Ellis Horwood, Chichester: 108-121.

Harland, R. 1992. Dinoflagellate cysts of the Quaternary System. *In:* Powell, A. J. (ed.). *A stratigraphic index of dinoflagellate cysts.* British Micropalaeontological Society Publications Series. Chapman and Hall, London, 253-272.

Hine, N. & Weaver, P.P.E. 1998. Quaternary. *In*: P.R. Bown (Ed.). *Calcareous Nannofossil Biostratigraphy.* British Micropalaeontological Society Publications Series/Kluwer Academic Publishers: 266-283.

King, C. 1989. Cenozoic of the North Sea. In Jenkins, D.G. & Murray, J.W. *Stratigraphical Atlas of fossil foraminifera, second edition*, 418-489 [Ellis Horwood, Chichester]

Mackensen, A., Sejrup, H.P. & Jansen, E., 1985. The distribution of living benthic foraminifera on the continental slope and rise off southwestern Norway. *Marine Micropaleontology*, 9, 275-306.

Martini, E. 1971. Standard Tertiary and Quaternary calcareous nannoplankton zonation. *In*: A. Farinacci (Ed.). *Proceedings of the Second Planktonic Conference Roma 1970*. Edizioni Tecnoscienza, Rome, **2**: 739-785.

Morkhoven, F.P.C.M. van, Berggren, W.A. & Edwards, A.S. 1986. Cenozoic cosmopolitan deep-water benthic foraminifera. *Bulletin des Centres de recherches Exploration-Production Elf-Aquitaine, Memoir* **11**, 412pp

Okada, H. & Bukry, D. 1980. Supplementary modification and introduction of code numbers to the low-latitude coccolith biostratigraphic zonation (Bukry, 1973; 1975). *Marine Micropaleontology*, **5**: 321-325.

Powell, A. J. 1992. Dinoflagellate cysts of the Tertiary System. *In:* Powell, A. J. (ed.). *A stratigraphic index of dinoflagellate cysts.* British Micropalaeontological Society Publications Series. Chapman and Hall, London, 155-251.

Qvale, G. & van Weering T.C.E. 1985. Relationship of surface sediments and benthic foraminiferal distribution patterns in the Norwegian Channel (Northern North Sea). *Marine Micropaleontology*, **9**, 469-488.

Riding, J. B. and Thomas, J. E. 1992. Dinoflagellate cysts of the Jurassic System. *In:* Powell, A. J. (ed.). *A stratigraphic index of dinoflagellate cysts.* British Micropalaeontological Society Publications Series. Chapman and Hall, London, 7-97.

Riding, J. B., Moorlock, B. S. P., Jeffery, D. H. and Hamblin, R. J. O. 1997. Reworked and indigenous palynomorphs from the Norwich Crag Formation (Pleistocene) of eastern Suffolk: implications for provenance, palaeogeography and climate. *Proceedings of the Geologists' Association,* **108,** 25-38.

Riding, J. B., Head, M. J. and Moorlock, B. S. P. 2000. Reworked palynomorphs from the Red Crag and Norwich Crag formations (Early Pleistocene) of the Ludham Borehole, Norfolk. *Proceedings of the Geologists' Association*, **111**, 161-171.

Riding, J.B., Williams, M & Wilkinson, I.P. 1999. An integrated micropalaeontological investigation of seven boreholes in the Faroes/Shetland are (1999 Rockall Consortium drilling Programme). *British Geological Survey Technical Report, Stratigraphy Series*, **WH99/112C**, 24pp.

Riding, J.B., Williams, M & Wilkinson, I.P. 1999. Micropalaeontological analyses of seven boreholes in the Faroes/Shetland area. *British Geological Survey Technical Report, Stratigraphy Series*, **WH99/113C**, 19pp.

Weston, J.F. 1985. Comparison between Recent benthic foraminiferal faunas of the Porcupine Seabight and Western Approaches continental slope. *Journal of Micropalaeontology*, **4**, 165-183.

Wilkinson, I.P. Calcareous microfaunas from the Rockall area and West of Shetlands. *British Geological Survey Technical Report, Stratigraphy Series*, **WH99/144C**, 10pp.

Appendix 1

Sample details

Samples and microfossil slides from the two boreholes were registered into the BGS Biostratigraphical collections, Keyworth, as follows:

Borehole 99/3

BGS Registration	Depth (m)
MPA49337	12.65
MPA49338	12.90
MPZ15027	28.81
MPA49339	31.85
MPA49340	34.22
MPZ15028	34.70
MPA49341	37.78
MPA49342	41.27
MPA49343	44.26
MPA49344	44.60
MPA49345	47.04
MPZ15031	50.87
MPZ15034	52.40
MPA49346	53.10
MPA49347	53.55
MPA49348	53.75

Borehole 99/6

BGS Registration	Depth (m)
MPA49349	3.80
MPA49350	4.65
MPZ15058	4.85
MPA49351	4.90
MPA49352	4.98
MPA49353	9.50
MPA49354	9.77
MPA49355	9.95
MPA49356	11.97
MPZ15059	13.91

Appendix 2

Additional notes

During analyses of the foraminifera, the following additional observations were made:

Borehole 99/3

BGS Registration	Depth (m)	
MPA49337	12.65	Small bivalve fragments and rare sponge spicules noted
MPA 49338	12.90	Small chips of bivalves are present.
MPA 49339	31.85	Small fragments of bivalve and echinoid spines seen.
MPA 49341	37.78	Small, rare bivalve fragments and black wood chips occur.
MPA 49348	53.75	Small bivalve chips are present.

Borehole 99/6

BGS Registration	Depth (m)	
MPA 49349	3.80	Rare bivalve chips and very rare wood chips were noted.
MPA 49354	9.77	Rare chips of black "coal" were seen.

Depth (metres)	*Cassidulina teretis*	*Globigerina bulloides*	*Neogloboquadrina pachyderma* (sinistral)	*Cassidulina laevigata*	*Cibicidoides* sp	*Melonis barleeanum*	*Elphidium excavatum clavatum*	*Trifarina fluens*	"*Arenobulimina*" sp	*Lenticulina* sp.	*Glomospira charoides*	*Bulimina marginata*	*Cibicides lobatulus*	*Triloculina trihedra*	*Cassidulina reniforme*	*Haynesina orbiculare*	*Quinqueloculina seminulum*	*Nonion labradoricum*	*Neogloboquadrina pachyderma* (dextral)	*Cibicides* cf *fletcheri*	*Bulimina gibba*	*Islandiella islandica*	*Elphidium asklundi*	*Paromalina crassa*	*Elphidium incerum*	*Elphidium groenlandicum*	*Virgulina loeblichi*	*Oolina* cf. *borealis*	*Ammonia batavus*	*Fissurina lucida*	*Spiroplectammina wrighti*	*Quinqueloculina agglutinans*	*Planulina ariminensis*	*Globigerinelloides*? Sp	*Guttulina* sp
12.65			R		VR								VR																						VR
12.9		R	R										VR							VR													R	VR	VR
28.81	R		R				R						R					VR								R	VR	VR	VR	VR	VR	VR			
31.85	R		R										VR				VR								VR	R									
34.22			A				VR						VR							VR	VR	VR	VR	VR											
34.7		VR	F			VR	VR					VR					VR	VR	VR																
37.78							VR																												
41.27		BARREN																																	
44.26		BARREN																																	
44.6		BARREN																																	
47.04	VR		A									VR				VR																			
50.87	VR		F			VR	R					VR	VR	VR	VR																				
52.4	C	VR	R	C					VR	VR	VR																								
53.1	F																																		
53.55	C		A	R	VR	R	R	VR																											
53.75	F	VR	R	R																															

VR= very rare
R= rare
F=frequent
C=common
A=abundant

Figure 1. Distribution of Foraminifera in Borehole 99/3

Depth (metres)	*Neogloboquadrina pachyderma* (sinistral)	*Cassidulina teretis*	*Cibicidoides* sp	*Ammobaculites* sp	"*Rhizammina*" sp	*Elphidium excavatum clavatum*	*Bulimina marginata*	*Neogloboquadrina pachyderma* (dextral)	*Cibicides lobatulus*	*Gavelinella thalmanni*	*Globorotalites michelinianus*	*Globigerina bulloides*	*Elphidium incertum*	*Pullenia bulloides*	*Buccella frigida*	*Ammonia batavus*	*Cassidulina globosa*	*Bulimina gibba*
3.8	A	R				F			F			R	R		VR	VR	VR	VR
4.65	A	R				R						VR	R	VR				
4.85	F	R				R			VR			R						
4.9	A						VR	VR	VR	VR	VR							
4.98	F	A				R												
9.5				VR	VR													
9.77	R	A	VR															
9.95	R	C																
11.97	BARREN																	
13.91	R																	

VR= very rare
R= rare
F=frequent
C=common
A=abundant

Figure 2. Distribution of Foraminifera in Borehole 99/6

		KEROGEN:	DARK BROWN WOOD	BROWN WOOD	VARIOUS PLANT TISSUES	PALYNOMORPHS	AMORPHOGEN	MINERAL GRAINS
Sample Number	Reg. No.	Depth (m)						
1	MPA 49337	12.65	P/R	P/R	P/R	P/C	P/R	R
2	MPA 49338	12.9	P	P	P	P/C	R/P	R
3	MPA 49339	31.85	C	P	P	C	P/C	R
4	MPA 49340	34.22	P	C	P/C	C/Ab	P/R	P/R
5	MPA 49341	37.78	C/Ab	P/C	P	C	P/R	C/Ab
6	MPA 49342	41.27	P/C	P	P/R	C	R/P	C/Ab
7	MPA 49343	44.26	C/P	P	P/R	C/Ab	R	R
8	MPA 49344	44.6	P	P/R	P	C/Ab	P/C	C/P
9	MPA 49345	47.04	P	P	P	C/Ab	P/C	R
10	MPA 49346	53.1	P	P/R	P	C	C	R
11	MPA 49347	53.25	P/C	P/R	P/C	C/Ab	R	R/P
12	MPA 49348	53.55	P/C	P	R	P	P/C	R

Figure 3. Distribution of major kerogen types and mineral grains in borehole 99/3
P-present R-rare C-common Ab-abundant

		PALYNOMORPHS:	QUATERNARY DINO. CYSTS	QUATERNARY POLLEN	PALAEOGENE	CRETACEOUS	JURASSIC	CARBONIFEROUS
Sample Number	Reg. No.	Depth (m)						
1	MPA 49337	12.65	C/Ab	R	R	absent	R	R
2	MPA 49338	12.9	R/P	R	absent	absent	R	P
3	MPA 49339	31.85	P	R	absent	absent	R	P/C
4	MPA 49340	34.22	P/C	R	R	R	R/P	P/C
5	MPA 49341	37.78	R/P	R	R	R	R	P/C
6	MPA 49342	41.27	R	R	absent	?	R	C/Ab
7	MPA 49343	44.26	R	R	absent	?	R	P/C
8	MPA 49344	44.6	R	R	R	R	R	C/Ab
9	MPA 49345	47.04	R	R	P/C	P/R	R/P	P
10	MPA 49346	53.1	R	R	absent	P	absent	P
11	MPA 49347	53.25	R	R	?	P/C	?	P
12	MPA 49348	53.55	R	R	?	R	?	R

Figure 4. Distribution of indigenous and reworked palynmorphs, by age, in borehole 99/3
P-present R-rare C-common Ab-Abundant

		KEROGEN:	DARK BROWN WOOD	BROWN WOOD	VARIOUS PLANT TISSUES	PALYNOMORPHS	AMORPHOGEN	MINERAL GRAINS
Sample No.	Reg. No.	Depth (m)						
13	MPA 49349	3.8	P/C	P/R	C	Ab/C	P/R	R
14	MPA 49350	4.65	Ab	P	P	C/Ab	absent	R
15	MPA 49351	4.9	P	R	R	C/Ab	R	P/R
16	MPA 49352	4.98	P/C	R	P	C/Ab	absent	R
17	MPA 49353	9.5	P	R	R	P	P	C/Ab
18	MPA 49354	9.77	Ab	C	C	Ac	absent	R
19	MPA 49355	9.95	C/P	R	P	C/P	P	R
20	MPA 49356	11.97	Ab/C	R	P	C	R	P

Figure 5. Distribution of major kerogen types and mineral grains in borehole 99/6
P-present R-rare C-common Ab-abundant

Figure 7a. BH99/6: NANNOFOSSIL RESULTS

(Jackie Burnett 5.00) Vertical stippling denotes stratigraphically-useful taxon; horizontal stippling denotes barren samples

REWORKED MESOZOIC TAXA

DEPTH	PRESERVATION	ABUNDANCE	TAXA	*Acuturris scotus*	*Ahmuellerella octoradiata*	*Ahmuellerella regularis*	*Arkhangelskiella confusa*	*Arkhangelskiella cymbiformis*	*Arkhangelskiella maastrichtiana*	*Biscutum* cf. *B. ellipticum*	*Biscutum ellipticum*	*Biscutum magnum*	*Biscutum melaniae*	*Biscutum notaculum*	*Braarudosphaera bigelowii*	*Broinsonia matalosa*	*Broinsonia parca expansa*	*Broinsonia parca parca*	*Broinsonia signata*	*Bukyrithus ambiguus*	*Calculites adolitus*	*Calculites obscurus*	*Calculites ovalis*	*Chiastozygus bifarius*	*Chiastozygus garrisonii*	*Chiastozygus litterarius*	*Chiastozygus platyrhethus*	*Cribrosphaerella ehrenbergii*	*Cretarhabdus conicus*	*Crucibiscutum hayi*	*Crucibiscutum* cf. *C. salebrosum*	*Cyclagelosphaera margerelii*	*Cyclagelosphaera rotaclypeata*	*Cylindralithus biarcus*	*Discorhabdus ignotus*	*Eiffellithus eximius*	*Eiffellithus gorkae*	*Eiffellithus turriseiffelii*	*Eprolithus apertior*	*Eprolithus floralis*	*Eprolithus moratus*	*Gartnerago obliquum*	*Gartnerago praeobliquum*	*Gartnerago segmentatum*	*Gartnerago theta*	*Hagius circumradiatus*	*Helenea chiasta*	*Helicolithus anceps*	*Helicolithus trabeculatus*	*Helicolithus turonicus*	*Kamptnerius magnificus*	*Lithastrinus grillii*	*Lithastrinus septenarius*	*Lithraphidites carniolensis*	*Lotharingius crucicentralis*	*Loxolithus armilla*	*Lucianorhabdus cayeuxii*	*Lucianorhabdus maleformis* long form	*Lucianorhabdus maleformis* short form	*Lucianorhabdus quadrifidus*	*Manivitella pemmatoidea*	*Markalius inversus*	*Marthasterites furcatus*	*Microrhantholithus obtusus*	*Microrhabdulus belgicus*	*Microrhabdulus decoratus*	*Microrhabdulus undosus*	*Micula concava*	*Micula cubiformis*
3.80m	P-M	L-M			R			R	R	F	F													R				F		R		F			F		F	F						F		R			R	R	F			R			F								R	R			
4.65m	P-M	M		R	R	F	R	F	F	F	R						R					F	R	F		R		F				R			R	R	R	F						F					F		F		R	F		R	F	R	R		R	R	R						
4.90m	BARREN																																																																				
4.98m	VP-P	VL			F			R	R							R												R					R									R		F																								R	
9.50m	VP-P	VL						F			F					R													R	R															R				?		R			R		?													
9.77m	VP-P	VL																														R												R																									
9.95m	P-M	L-M						R	R	F												R						R				R																			F			F													R				
11.97m	BARREN																																																																				

Figure 7b. BH99/3: NANNOFOSSIL RESULTS

DEPTH	PRESERVATION	ABUNDANCE	TAXA	*Acuturris scotus*	*Ahmuellerella octoradiata*	*Ahmuellerella regularis*	*Arkhangelskiella confusa*	*Arkhangelskiella cymbiformis*	*Arkhangelskiella maastrichtiana*	*Biscutum* cf. *B. ellipticum*	*Biscutum ellipticum*	*Biscutum magnum*	*Biscutum melaniae*	*Biscutum notaculum*	*Braarudosphaera bigelowii*	*Broinsonia matalosa*	*Broinsonia parca expansa*	*Broinsonia parca parca*	*Broinsonia signata*	*Bukyrithus ambiguus*	*Calculites adolitus*	*Calculites obscurus*	*Calculites ovalis*	*Chiastozygus bifarius*	*Chiastozygus garrisonii*	*Chiastozygus litterarius*	*Chiastozygus platyrhethus*	*Cribrosphaerella ehrenbergii*	*Cretarhabdus conicus*	*Crucibiscutum hayi*	*Crucibiscutum* cf. *C. salebrosum*	*Cyclagelosphaera margerelii*	*Cyclagelosphaera rotaclypeata*	*Cylindralithus biarcus*	*Discorhabdus ignotus*	*Eiffellithus eximius*	*Eiffellithus gorkae*	*Eiffellithus turriseiffelii*	*Eprolithus apertior*	*Eprolithus floralis*	*Eprolithus moratus*	*Gartnerago obliquum*	*Gartnerago praeobliquum*	*Gartnerago segmentatum*	*Gartnerago theta*	*Hagius circumradiatus*	*Helenea chiasta*	*Helicolithus anceps*	*Helicolithus trabeculatus*	*Helicolithus turonicus*	*Kamptnerius magnificus*	*Lithastrinus grillii*	*Lithastrinus septenarius*	*Lithraphidites carniolensis*	*Lotharingius crucicentralis*	*Loxolithus armilla*	*Lucianorhabdus cayeuxii*	*Lucianorhabdus maleformis* long form	*Lucianorhabdus maleformis* short form	*Lucianorhabdus quadrifidus*	*Manivitella pemmatoidea*	*Markalius inversus*	*Marthasterites furcatus*	*Microrhantholithus obtusus*	*Microrhabdulus belgicus*	*Microrhabdulus decoratus*	*Microrhabdulus undosus*	*Micula concava*	*Micula cubiformis*
12.65m	VP-M	L		R	R			R		F			R															F							R			F		R			R					R			R																		
12.90m	VP-M	VL-L						F	R		F			F								R								R							R	F																															
31.85m	VP-M	L-M		R	F		R		F	F												F						F				R			F			F		R								R			F			R															
34.22m	VP-M	L-M		R		F		R		F	F							F			R	F		R				F				F	F		R	R	F	F		F				F							F			R			F	R									F		R
37.78m	VP-M	L-M			R			F		F	F	R				R				F		F						F	R			F	R	R	R	F		F			R			F			R	R	R		F			R			F			F	F						R		
41.27m	VP-M	L-M			R						F											R						F			R	F			F			F						F					F								R							R					
44.26m	VP-M	VL-L						R	R	R	F											R		R	R		R	R				R	F					F						R							R			R			F				R								
44.60m	VP-M	VL-L		R	R						F											R		R								F						F						R			?					R		R			F												
47.04m	VP-M	L-M		R	F			F		R	F					R		?	R			F	R	F								F				F		R		R				R					R		F			R			F	R		R	R								
53.10m	VP-M	L-M			F		R	R		F	R				R							R						R				F	R			R								F				R	R		R			R			R				R		R						
53.55m	VP-M	L-M						F	F	F	F															R		F								R	R	R										F	R					R			R					R							
53.75m	VP-M	L							F							R			R					R												R		F											F		F			R	R		R										R		

REWORKED MESOZOIC TAXA continued

Micula murus	*Micula staurophora*	*Micula swastica*	*Misceomarginatus pleniporus*	*Nannoconus* sp. x-section	*Neocrepidolithus cohenii*	*Nephrolithus frequens*	*Octolithus multiplus*	*Orastrum campanensis*	*Orastrum colligatum*	*Parhabdolithus liasicus*	*Placozygus* cf. *P. fibuliformis*	*Placozygus fibuliformis*	*Prediscosphaera arkhangelskyi*	*Prediscosphaera* cf. *P. grandis*	*Prediscosphaera columnata*	*Prediscosphaera cretacea*	*Prediscosphaera grandis*	*Prediscosphaera incohatus*	*Prediscosphaera majungae*	*Prediscosphaera ponticula*	*Prediscosphaera spinosa*	*Prediscosphaera stoveri*	*Radiolithus planus*	*Reinhardtites anthophorus*	*Reinhardtites levis*	*Repagulum parvidentatum*	*Retecapsa angustiforata*	*Retecapsa crenulata*	*Retecapsa surirella*	*Rhagodiscus achlyostaurion*	*Rhagodiscus angustus*	*Rhagodiscus asper*	*Rhagodiscus plebeius*	*Rotelapillus crenulatus*	*Rucinolith us* sp.	*Scampanella* sp.	*Schizosphaerella punctulata*	*Seribiscutum gaultensis*	*Seribiscutum primitivum*	*Staurolithites crux*	*Staurolithites ellipticus*	*Staurolithites imbricatus*	*Staurolithites laffittei*	*Staurolithites mielnicensis*	*Tegumentum stradneri*	*Tetrapodorhabdus decorus*	*Thoracosphaera saxea*	*Tranolithus orionatus*	*Tubodiscus* sp.	*Tuborhabdus patulus*	*Watznaueria barnesiae*	*Watznaueria biporta*	*Watznaueria britannica*	*Watznaueria manivitiae s.l.*	*Watznaueria manivitiae s.s.*	*Zeugrhabdotus bicrescenticus*	*Zeugrhabdotus biperforatus*	*Zeugrhabdotus diplogrammus*	*Zeugrhabdotus embergeri*	*Zeugrhabdotus erectus* J. & K. forms
	F	R		R		R	R					R								F	R	F		R	R	R		F									R						R					F			F	R	F	F		F				
	F					?					R			R	R	F	F			F	F	R		F	F			F	R									R				R	F	R				F			F	R	F	F						
											R									F						R		R										R				R						R			F		R					R		
																				R		R						R											R				R																	
	F												R				R			F								R																							F			R						
	R													F	R	R	R			F		R				R		R								R							R	R				R					F	F					?	
	R				R				R			R				R	R			F	R				R			R	R								R	R										R			F		F	F		R				R
	R				R	R						R				R	R			F																						R					R	R			F	R	R	F						
						R	R				R						R			F	R	F		?		F	R	F															R					F			F		F	F	R					
	F		R								F			R			F			F		R		F		F	F	F				R	R	R									F	R				F			F	R	F	F	R	F	R			F
	F										F	F	R			F	R			F				F	R		F	F			R	F		R									F			F	R	F			F		F	F		F				
	F										R	R								R				R				F		R		F		R	R								F		R		R	F			F		F	F				R		F
	F			R	R														R	F					F			R				R																F			F		F	R	R					F
	F													R						F					F	R	F	F						R					R	R					R		R	F	R		F		F	F	R					F
	F													F			F			F					F	R		F				R									R	R					R	F			F	R	C	F	R	F				F
	F																			F	R	R	R	R		R		F				R											R				R	R			F		F	F		R				
R	F															F		R	R	F		F			R	F		F			R												F	R				F			F	R	F	F		R		R		R
	F							R		R		R			R	R				F	F	R			R	R	R	F	R																		R	F		R	F		F							

TERTIARY (REWORKED) & QUATERNARY TAXA

Zeugrhabdotus noeliae	*Zeugrhabdotus scutula*	*Zeugrhabdotus sigmoides*	*Zeugrhabdotus* cf. *Z. trivectis*	*Chiasmolithus grandis*	*Clausicoccus fenestratus*	*Coccolithus pelagicus*	*Coronocycl* us sp.	*Cruciplacolithus edwardsii*	*Cruciplacolithus tenuis*	*Cyclicargolithus floridanus*	*Discoaster tiradiatus* ?	*Discoaster wemmelensis*	*Emiliania huxleyi*	*Ericsonia formosa*	*Gephyrocapsa aperta*	*Gephyrocapsa ericsonii*	*Gephyrocapsa muelleri*	*Gephyrocapsa oceanica*	*Helicosphaera carteri*	*Helicosphaera euphratis*	*Neosphaera coccolithomorpha* ?	*Pontosphaera discopora*	*Pontosphaera multipora*	*Prinsius dimorphosus*	*Prinsius martinii*	*Pseudoemiliania lacunosa* ?	*Pseudoemiliania ovata*	*Reticulofenestra minuta*	*Reticulofenestra minutula*	*Reticulofenestra pseudoumbilicus*	*Reticulofenestra umbilicus*	*Sphenolithus abies*	*Sphenolithus* us *delphix* ?	*Sphenolithus* us *moriformis*	*Sphenolithus* sp. indet.	*Transversopontis* sp.	*Umbilicosphaera jafari* ?	NANNOFOSSIL EVENT	NANNOFOSSIL ZONE after Martini (1971: NN) & Okada & Bukry (1980: CN)	STAGE after Martini (1971)	DEPTH
					1	#		R	R	3		1	**8**	1	#	#	4					1		R	R	1	6	12	4	4	R	R				2	8	*E. huxleyi* present	NN21/ CN15	UPPER PLEISTOCENE	3.80m
R		R				6							**#**		7	#											8	4								1	1				4.65m
																																						INDETERMINATE			4.90m
																																									4.98m
R						1							**1**																									*E. huxleyi* present	NN21/ CN15	UPPER PLEISTOCENE	9.50m
						1										2																			2						9.77m
					1					1			**#**	1	#	#												46			R										9.95m
																																						INDETERMINATE			11.97m
R						3				1			**#**	1	8	4	5										2	2		1								*E. huxleyi* present	NN21/ CN15	UPPER PLEISTOCENE	12.65m
F						5							**1**		9	5												4		1											12.90m
						8				1	1		**#**		8	8	8										1	6		3											31.85m
		R		1		#				9			**#**		#	#	#											14													34.22m
R		R	R			7				1			**6**		#	5	3										1	4		2											37.78m
			R			1				1			**1**		5	4												2		3			1								41.27m
	R					3				1					3	6												6		2											44.26m
	R	R				1									5	3														2											44.60m
						2				1			**6**		5	8													4	10				1	1						47.04m
F						5				2						3						1				2		10	1	1							1				53.10m
	R					2	1			1			**5**		4	5	2	1		1	1		1				5	1	10	7		1				2	1				53.55m
						3			R	1			**1**			3			2			1				3	2									1					53.75m

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Dr. Dan Evans
British Geological Survey
West Mains Road
Edinburgh
EH9 3LA
United Kingdom

07 November 2000

Results of Radiocarbon dating of samples from Boreholes 99/3 and 99/6

Dear Dr. Evans,

Please find enclosed the results of the radiocarbon dating of the above samples.

The samples were cleaned with 15 % H_2O_2 in an ultrasonic bath to remove adhering dust and detrital carbonate as well as organic surface coating. The CO_2 was liberated from the sample with 100 % phosphoric acid at 90 °C. The CO_2 was reduced with H_2 over about 2 mg of Fe powder as catalyst, and the resulting carbon/iron mixture was pressed into a pellet in the target holder.

The ^{14}C concentration of the samples was measured by comparing the simultaneously collected ^{14}C, ^{13}C, and ^{12}C beams of each sample with those of Oxalix Acid standard CO_2 and Eemian foraminifera. Conventional ^{14}C ages were calculated with a $\delta^{13}C$ correction for isotopic fractionation based on the $^{13}C/^{12}C$ ratio measured by our AMS-system simultaneously with the $^{14}C/^{12}C$ ratio (note: This $\delta^{13}C$ includes the effects of fractionation during graphitization and in the AMS-system and, therefore, cannot be compared with $\delta^{13}C$ values obtained per mass spectrometer on CO_2). For the determination of our measuring uncertainty (standard deviation σ) we observe both the counting statistics of the ^{14}C measurement and the variability of the interval results that, together, make up one measurement. The larger of the two is adopted as measuring uncertainty. To this we add the uncertainty connected with the subtraction of our "blank". As reference material for blank correction we used marine foraminifera from MIS 12 which yielded a pMC of 0.21±0.02 (49710 +670 /-620 BP). As background does not follow Poisson statistics we use an empirical uncertainty of ±1/3 of the measured background. The quoted 1σ uncertainty is thus our best estimate for the full measurement and not just based on counting statistics. "Conventional Age" according to Stuiver and Polach, Radiocarbon **19**/3 (1977), 355. We did not apply the global 400-yr reservoir age correction, as the preferred local value may be different.

Both samples yielded about the minimum amount of carbon that is required for a precise measurement and thus sufficient beam in the AMS instrument. The $\delta^{13}C$ values are in the normal range and do not indicate any non-correctable isotope fractionation during measurement. The results are therefore reliable. Both samples have pMC values smaller than their uncertainties, and we therefore cannot state finite ages. The minimum ages are based on the pMC of the samples plus 2 standard deviations giving a 98 % probability that the sample is older than the stated age.

Please don't hesitate to contact me should you have any further questions regarding these measurements.

Yours sincerely

(Pieter M.Grootes)

Copy to:
Dr. Antoon Kuijpers
Geological Survey of Denmark and Greenland
Thoravej 8
DK-2400 Copenhagen NV
Denmark

	Corrected pMC†	Conventional Age	δ13C ‡
Borehole 99/3 Depth 34.30 – 34.44m (KIA 12046. MPA 49662, 1.1 mg C)	0.00 ± 0.07	> 52900 BP	0.82 ± 0.09 ‰
Borehole 99/6 Depth 9.50 – 9.65m (KIA 12047. MPA 49664, 0.8 mg C)	0.00 ± 0.07	> 52890 BP	-1.13 ± 0.11 ‰

† "Corrected pMC" indicates the fraction of modern (1950) carbon corrected for fractionation using the ^{13}C measurement
‡ Please note that the $\delta\ ^{13}C$ includes the fractionation occurring in the sample preparation as well as in the AMS measurement and therefore cannot be compared to a mass-spectrometer measurement.